FINAL REPORT
LTPP PROFILER COMPARISON - 2013

July 2014

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16. Abstract
This report documents the comparison of the LTPP International Cybernetics Corporation (ICC) and the Ames inertial profilers recently purchased by the LTPP program. The review was performed to compare and contrast the data collected by the two models of inertial profilers and understand how the data may be affected by the equipment change. The comparisons are based on a set of concurrent runs made on selected test sections by the LTPP North region and Western region. Runs were made at sites selected by the regions representing different levels of roughness on both asphalt and Portland cement concrete surfaces. These data were compared using a variety of methods. The IRI were observed to be similar between the two profilers with differences in longitudinal profiler primarily occurring in wavelengths shorter than 0.02 m.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
AIMS	Ancillary Information Management System
DMI	Distance Measurement Instrument
FHWA	Federal Highway Administration
GPS	General Pavement Studies
ICC	International Cybernetics Corporation
IRI	International Roughness Index
LTPP	Long Term Pavement Performance
PCC	Portland Cement Concrete
PSD	Power Spectral Density
RSC	Regional Support Contractor
SPS	Specific Pavement Studies
TSSC	Technical Services Support Contractor

CHAPTER 1 – INTRODUCTION

In the Long Term Pavement Performance (LTPP) Program, longitudinal profile measurements at pavement test sections and weigh-in-motion traffic scales are collected by the Regional Support Contractors (RSCs). The LTPP program has been collecting longitudinal profile data since 1989. These first data sets were collected using KJ Law DNC690 model profilers. These profilers were equipped with optical height sensors. The first set of comparisons of the profilers was conducted in 1991. This comparison used a Dipstick as the reference device and the basis of comparison was predominately based upon comparisons of the International Roughness Index (IRI). That comparison illustrated that 95 percent of the average IRI values from all runs were within 2.6 percent of the overall average IRI.

In 1996 the program purchased four KJ Law T6600 model inertial profilers to replace the DNC690 profilers that had been used since 1989. The T6600 model profilers were equipped with infrared height sensors. These sensors were less susceptible to interference with data collection caused by ambient light and allowed for increased frequency of data collection. At that time a comparison was completed of the T6600 profilers and the DNC690 profilers. That comparison was performed by each region individually. Each region identified two asphalt and two concrete sections to use for the comparison. Data were collected using a Dipstick as well as both the T6600 and DNC690 profilers.

The program purchased new profilers from International Cybernetics Corporation (ICC) in 2002. At that time a new set of comparisons were performed between the ICC and KJ Law T6600 profilers. A set of sections was selected to be used by all regions for this comparison. Five sections were selected including two asphalt, two concrete and one chip seal surface. This comparison noted that for 70 percent of cases differences in IRI were within ± 0.10 m/km.

In early 2013, the inertial profilers used by the RSCs were replaced. From June 2002 to early 2013, MDR 4083 inertial profilers manufactured by International Cybernetics Corporation (ICC) were used by LTPP to collect longitudinal profile data. These profilers were equipped with three laser sensors that collect data in the left and right wheelpaths, and center of the lane. The ICC inertial profilers were replaced with inertial profilers developed by Ames Engineering in April 2013. Similar to the ICC profilers, the Ames profilers are equipped with three laser sensors that collect longitudinal profile data in the left and right wheelpaths and center of the lane.

Acceptance testing of the four Ames profilers was completed in February 2013. The acceptance testing was performed on several sections of different surface material, texture and levels of roughness. Measurements from the profilers were compared against a reference device for acceptance purposes.

Since comparisons between the ICC and Ames profilers were not included as part of the acceptance testing, comparison measurements were performed separately by the North and Western regions. The ICC profiler previously operated in the Southern region was no longer operational and could not be included in the comparison.

CHAPTER 2 – TEST PLAN

In the North region, seven (7) runs were completed on each of four (4) test sections as follows:

1. Smooth AC (Aero Drive): Data collected at 35 mph
2. Rough AC (Lawrence Bell Drive): Data collected at 35 mph and 50 mph
3. Rough PCC1 (Lake Ontario State Parkway Westbound): Data collected at 35 mph and 50 mph
4. Rough PCC2 (Lake Ontario State Parkway Eastbound): Data collected at 35 mph and 50 mph

Additionally, the North region completed data collection on two of the sections used for the initial profiler acceptance in April 2013. Specifically, nine (9) runs were completed with the ICC profiler and five (5) runs with the Ames profiler on Texas Acceptance Sections 1 and 2.

In the Western region, testing was carried out on three (3) test sections as follows:

1. Smooth AC: Data collected at 35 mph and 50 mph
2. Rough AC: Data collected at 35 mph and 50 mph
3. Rough PCC: Data collected at 50 mph and 65 mph

With the Western region, five (5) repeat measurement passes were completed on most of the test sections at each speed. The exceptions are that data set from the Ames profiler data on the rough PCC section included only the left and center sensors, and the ICC profiler completed only four successful runs on the Rough PCC section at 65 mph. The Rough PCC section in the Western region had a known International Roughness Index (IRI) value of at least 6.0 m/km in the right wheelpath which was too large the Ames sensor to measure. The ICC unit completed four successful runs on the Rough PCC section before it was no longer operable.

CHAPTER 3 – IRI COMPARISON

Table 3.1 presents the average IRI values for the sites from the North region and Table 3.2 the average IRI values for the sites from the Western region. The IRI was computed for each of the full test section profile measurements contained in the section for each run using the ProVAL software.

Table 3.1. Comparison of Average IRI Values from North Region

Section	Speed	Sensor	Ames Profiler		ICC Profiler	
			Mean, m/km	Std Dev, m/km	Mean, m/km	Std Dev, m/km
Smooth AC	35 mph	Left	1.39	0.04	1.32	0.01
		Right	1.34	0.04	1.47	0.01
Rough AC	35mph	Left	3.20	0.24	3.89	0.34
		Right	3.24	0.09	3.45	0.06
	50 mph	Left	3.00	0.09	3.83	0.25
		Right	3.10	0.09	3.44	0.04
Rough PCC1	35 mph	Left	2.37	0.07	2.78	0.06
		Right	2.37	0.04	2.42	0.08
	50 mph	Left	2.44	0.06	2.76	0.04
		Right	2.28	0.07	2.38	0.04
Rough PCC2	35 mph	Left	2.92	0.09	3.24	0.06
		Right	2.32	0.05	2.56	0.05
	50 mph	Left	2.96	0.11	3.24	0.03
		Right	2.40	0.05	2.64	0.05
Texas Acceptance Section 1	50 mph	Left	1.01	0.02	1.03	0.02
		Right	1.23	0.04	1.24	0.04
Texas Acceptance Section 2	50 mph	Left	2.05	0.02	2.19	0.03
		Right	2.32	0.02	2.40	0.04

The observed differences in the IRI may be due to differences in the data collected by the vehicles. They may also be due to small differences in the vehicles which would result in the driver collecting a slightly different path along the test section. Additional review of the data is required to understand the implications of the differences observed in the average IRI values.

Table 3.2. Comparison of Average IRI Values from Western Region

Section	Speed	Sensor	Ames Profiler		ICC Profiler	
			Mean, m/km	Std Dev, m/km	Mean, m/km	Std Dev, m/km
Smooth AC	35 mph	Left	0.62	0.01	0.66	0.01
		Right	0.85	0.01	0.86	0.03
	50 mph	Left	0.63	0.01	0.64	0.01
		Right	0.84	0.03	0.85	0.03
Rough AC	35 mph	Left	2.74	0.13	2.64	0.24
		Right	4.76	0.14	4.57	0.14
	50 mph	Left	2.63	0.11	2.59	0.25
		Right	4.67	0.21	4.37	0.10
Rough PCC	50 mph	Left	2.04	0.10	2.27	0.15
		Right	-	-	7.39	1.26
	65 mph	Left	2.04	0.14	2.15	0.31
		Right	-	-	7.45	1.17

To examine the statistical significance of the differences in IRI computed between the ICC and Ames profile measurements, a Student's t-test was used to compare the averages for each section-speed combination by wheelpath. This test evaluates the differences in the distributions of the IRIs from the multiple runs. Table 3.3 presents the results of the t-test comparisons. This presents the absolute value of the difference between the averages, the probability that the distributions are statistically the same (p-value), and whether or not that probability is statistically significant (0.05 significance level). The smaller the p-value, the less likely the distributions are equivalent. A "Yes" in the "Statistically Significant?" column indicates that the average differences are statistically significant, or the difference is significant relative to magnitude of run-to-run variability. A "No" indicates the differences between the averages were not statistically different, i.e. the measurements are equal from a statistical distribution viewpoint.

Table 3.3. t-test Comparison of IRI Values by Section

Region	Section	Speed	Sensor	Average Difference, m/km	p-value	Statistically Significant?
North	Smooth AC	35 mph	Left	0.07	0.01	Yes
			Right	0.13	0.0002	Yes
	Rough AC	35 mph	Left	0.69	0.0012	Yes
			Right	0.21	0.0004	Yes
		50 mph	Left	0.83	8.69×10^{-5}	Yes
			Right	0.34	1.46×10^{-5}	Yes
	Rough PCC 1	35 mph	Left	0.41	9.17×10^{-8}	Yes
			Right	0.05	0.22	No
		50 mph	Left	0.31	1.45×10^{-7}	Yes
			Right	0.10	0.010	Yes
	Rough PCC 2	35 mph	Left	0.32	7.11×10^{-6}	Yes
			Right	0.24	1.05×10^{-6}	Yes
		50 mph	Left	0.29	0.0002	Yes
			Right	0.23	2.04×10^{-6}	Yes
	Texas Acceptance Section 1	50 mph	Left	0.02	0.15	No
			Right	0.02	0.54	No
	Texas Acceptance Section 2	50 mph	Left	0.14	0.00015	Yes
			Right	0.09	0.0055	Yes
Western	Smooth AC	35 mph	Left	0.04	9.2×10^{-5}	Yes
			Right	0.01	0.49	No
		50 mph	Left	0.01	0.086	No
			Right	0.00	0.79	No
	Rough AC	35 mph	Left	0.11	0.41	No
			Right	0.19	0.070	No
		50 mph	Left	0.05	0.73	No
			Right	0.30	0.03	No
	Rough PCC	50 mph	Left	0.23	0.026	No
		65 mph	Left	0.11	0.49	No

As shown for the 18 comparisons in table 3.3 from the North region profilers, 16 IRI comparisons (89%) had statistically significant different average IRI values as computed from the ICC and Ames profiles.

For the Western region profiler comparison, significant statistical difference were indicated for only the left wheelpath sensor on the smooth AC test section at a measurement speed of 35-mph.

A common problem with using statistical test of significance is that the computation is based on the variability in the test data. Sometimes small differences in mean values can be judged to be significantly different if the variance associated with each mean is very small. Likewise large differences in mean values can be found to not be statistically significant different if the associated variances are large.

Engineering significance is based on the magnitude of the mean difference judged against an appropriate measure.

For this effort we used as an indication engineering significance based on pay factors that highway agencies use related to pavement smoothness in terms of IRI. One practice is to use 0.32-m/km interval between bonus/penalty levels of IRI. Based on this IRI interval for pay factors, a reasonable estimate of engineering significance is half of the interval, or 0.16 m/km. A way to interpret this level of significance is that if a difference in IRI due to the measurement device that equal or exceeds ½ of the pay factor interval level, then that is a difference of engineering significance.

Using this definition of engineering significance, in table 3.3 the two cells in the Western region with greater than a 0.2 m/km IRI are now significant, and the cell with a difference of only 0.05 m/km IRI is no longer significant. Additionally, the smooth section and the Texas Acceptance sections from the North region comparisons are no longer significant.

CHAPTER 4 – PROFILE PLOTS

A common way to perform a comparison between different longitudinal pavement profiler devices is to plot the reported wheelpath elevations in the data file against each other. The longitudinal profile measurements from the left wheelpath from the North region are illustrated in figures 4.1 through 4.9, and the Western region in figures 4.10 to 4.15. For each section, only the left sensor was plotted as differences observed between the devices should be similar between the left and right sensors. Each graph also shows the elevations from multiple runs of each device. Note, the legend identifies each profile with the word "full" indicating that the data were not further filtered as part of preparing the graph.

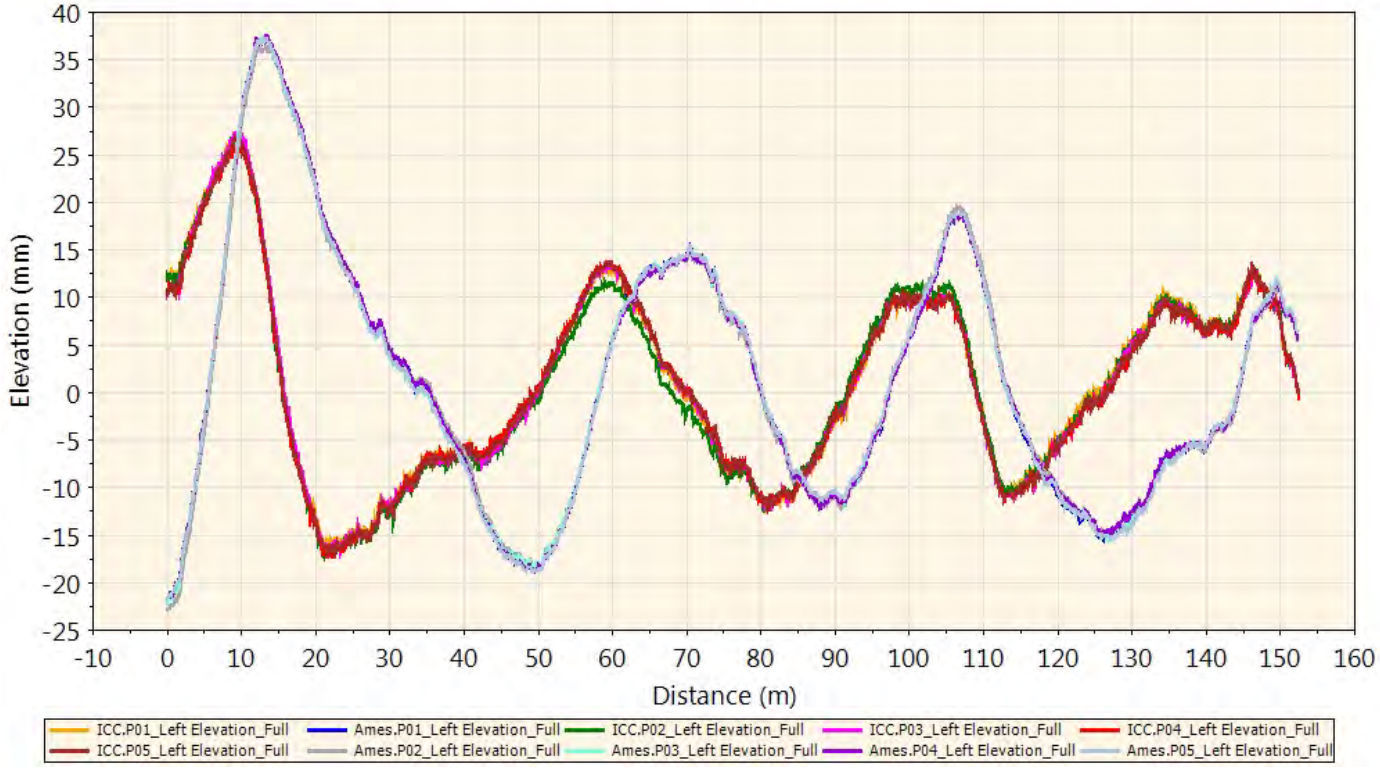

Figure 4.1. North Region Smooth AC, 35 mph, Left Sensor

From a simple inspection, the profile plots indicate large differences in the elevation data collected by the Ames and ICC profilers. However, closer inspection illustrates that many of the small events within the data may be observed within both sets of profiles. For example in figure 4.2, there are a series of dips that may be observed in profiles collected by the Ames and the ICC profiler. The dips observed at locations such as those at 25 m or 140 m are observed in both sets of profiles; however, the elevation from which those dips occur (not the actual size of the dip) is not the same for the two sets of profiles.

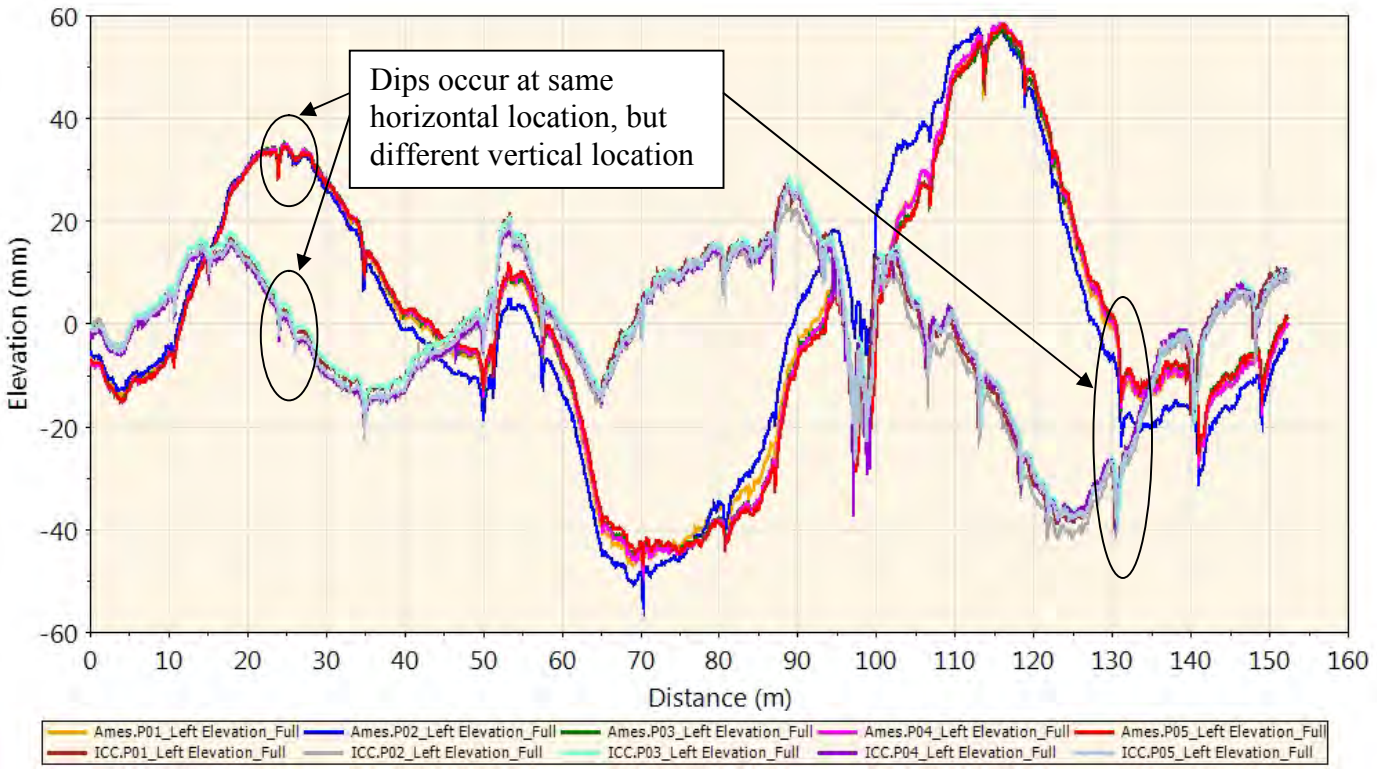

Figure 4.2. North Region Rough AC, 35 mph, Left Sensor

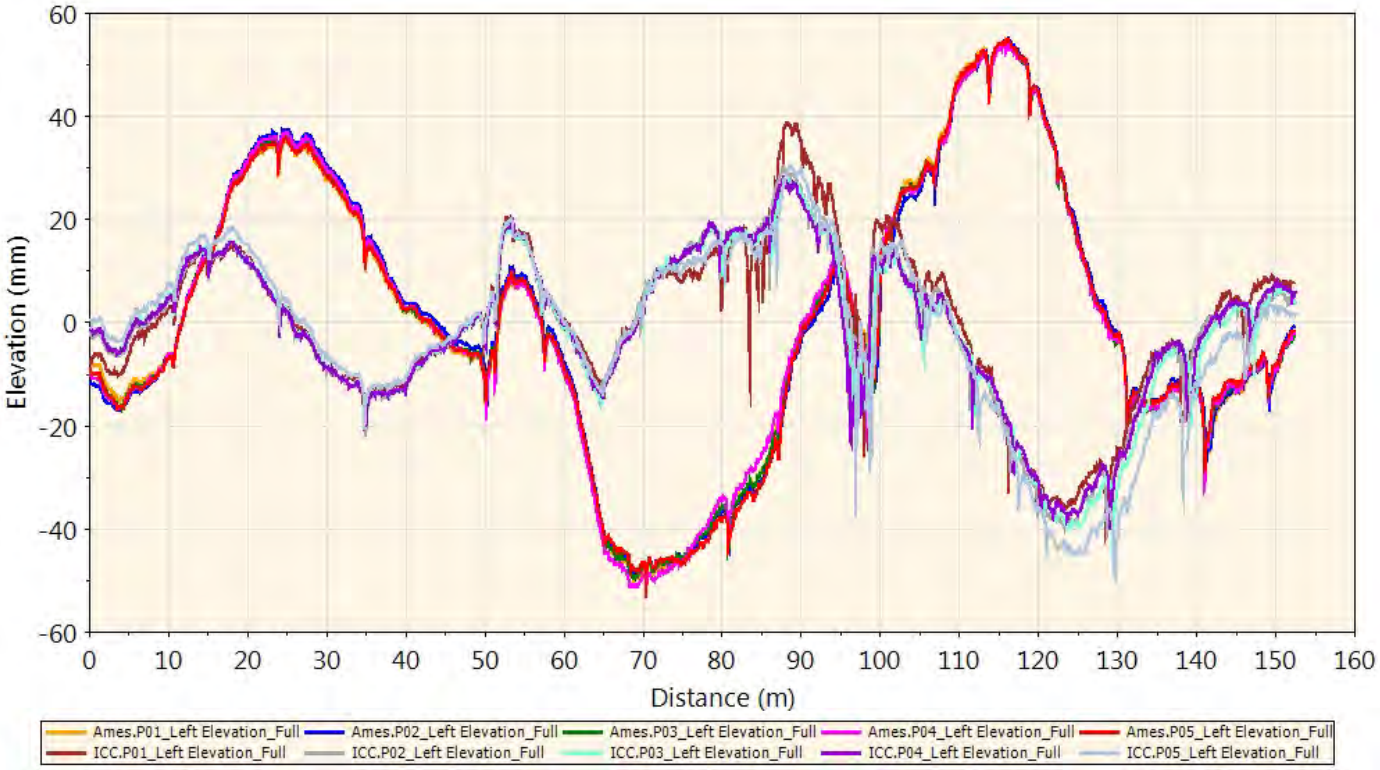

Figure 4.3. North Region, Rough AC, 50 mph, Left Sensor

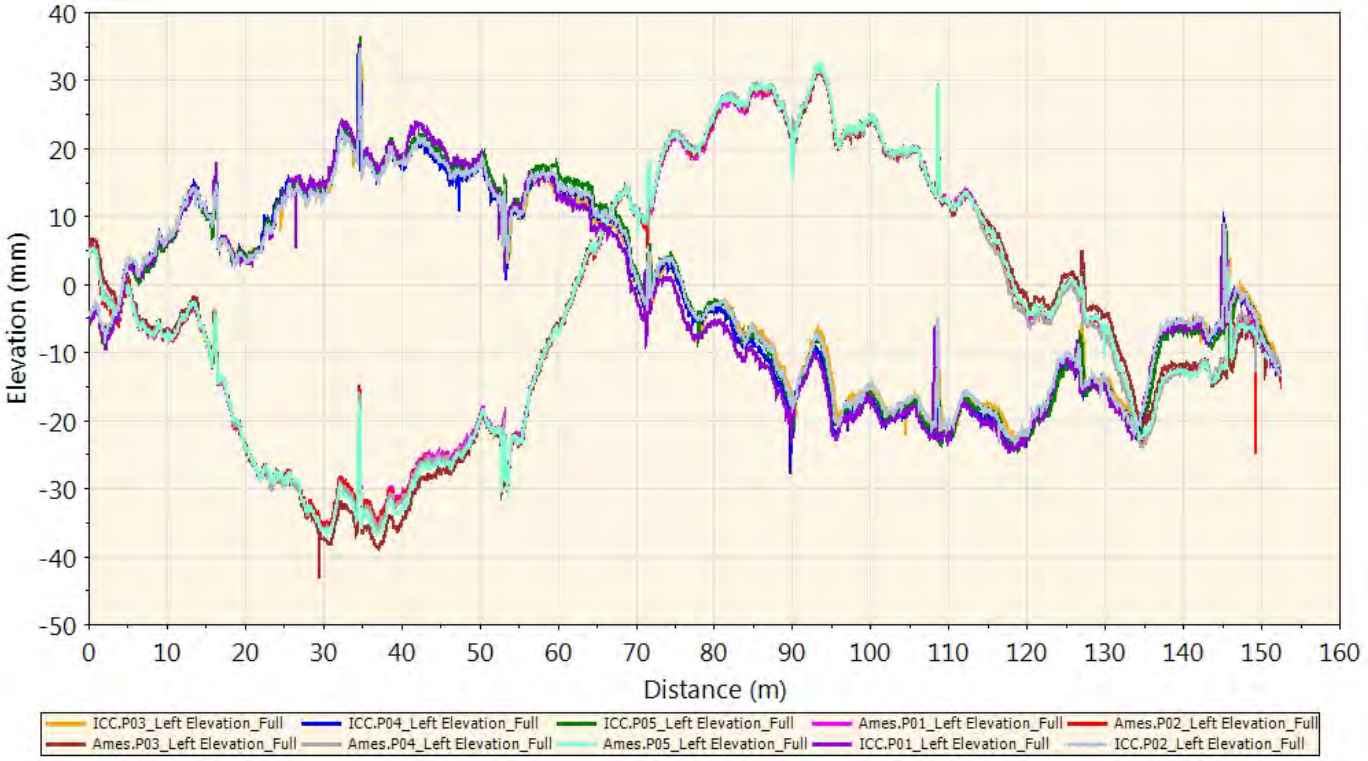

Figure 4.4. North Region, Rough PCC Section 1, 35 mph, Left Sensor

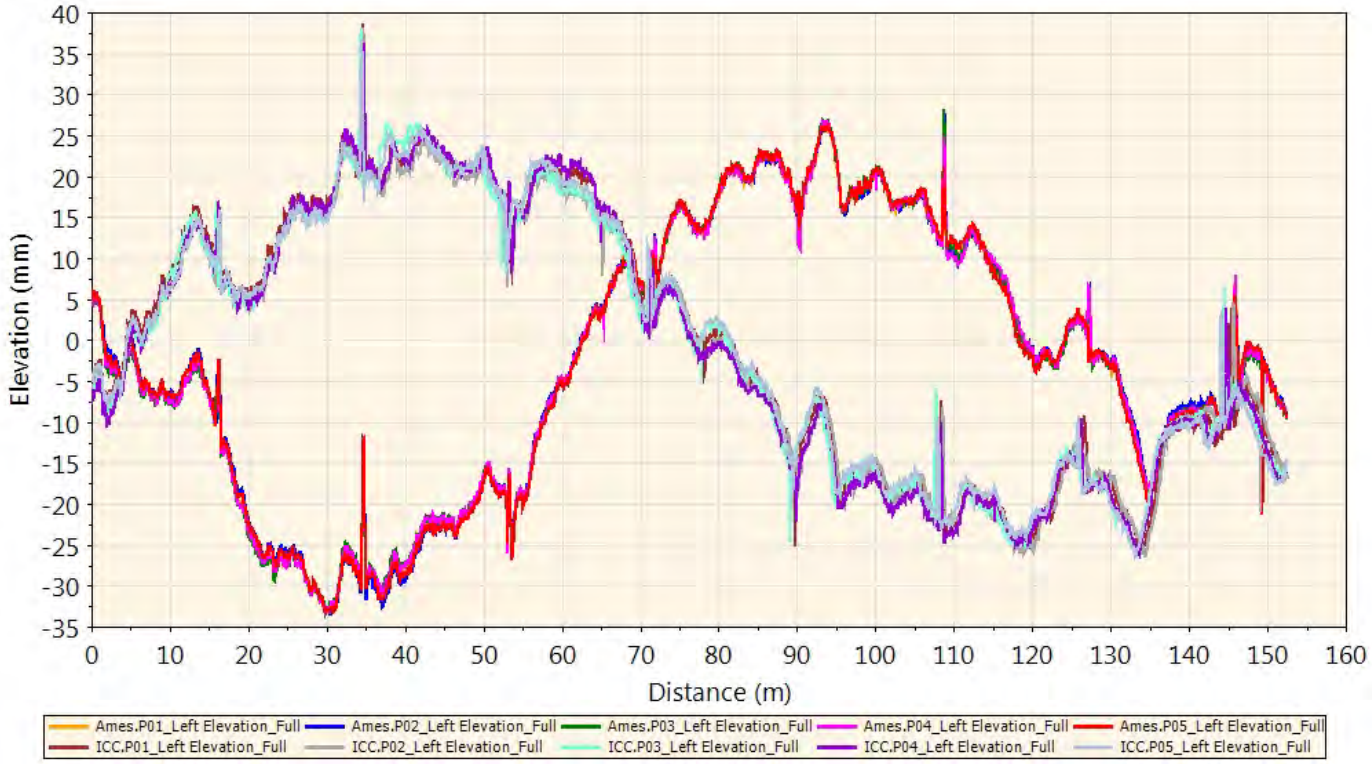

Figure 4.5. North Region, Rough PCC Section 1, 50 mph, Left Sensor

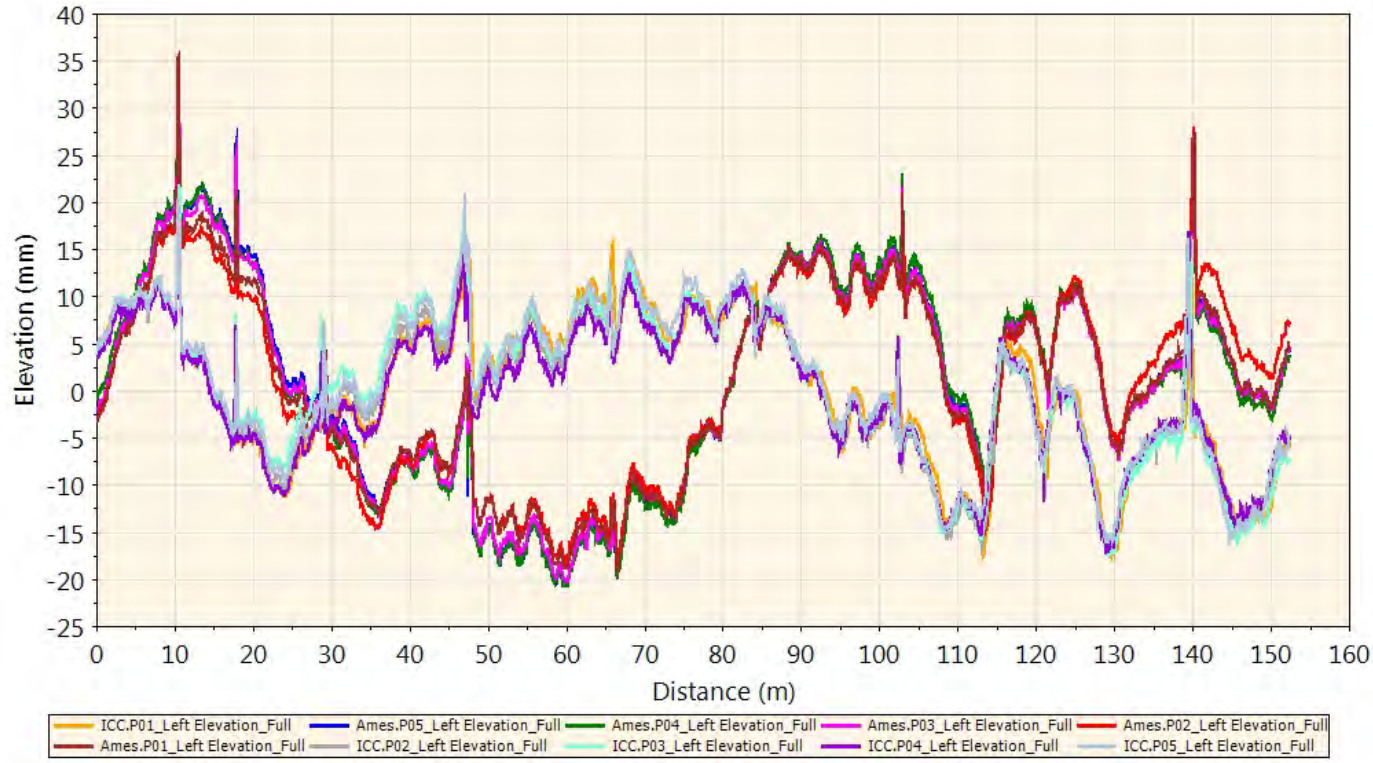

Figure 4.6. North Region, Rough PCC Section 2, 35 mph, Left Sensor

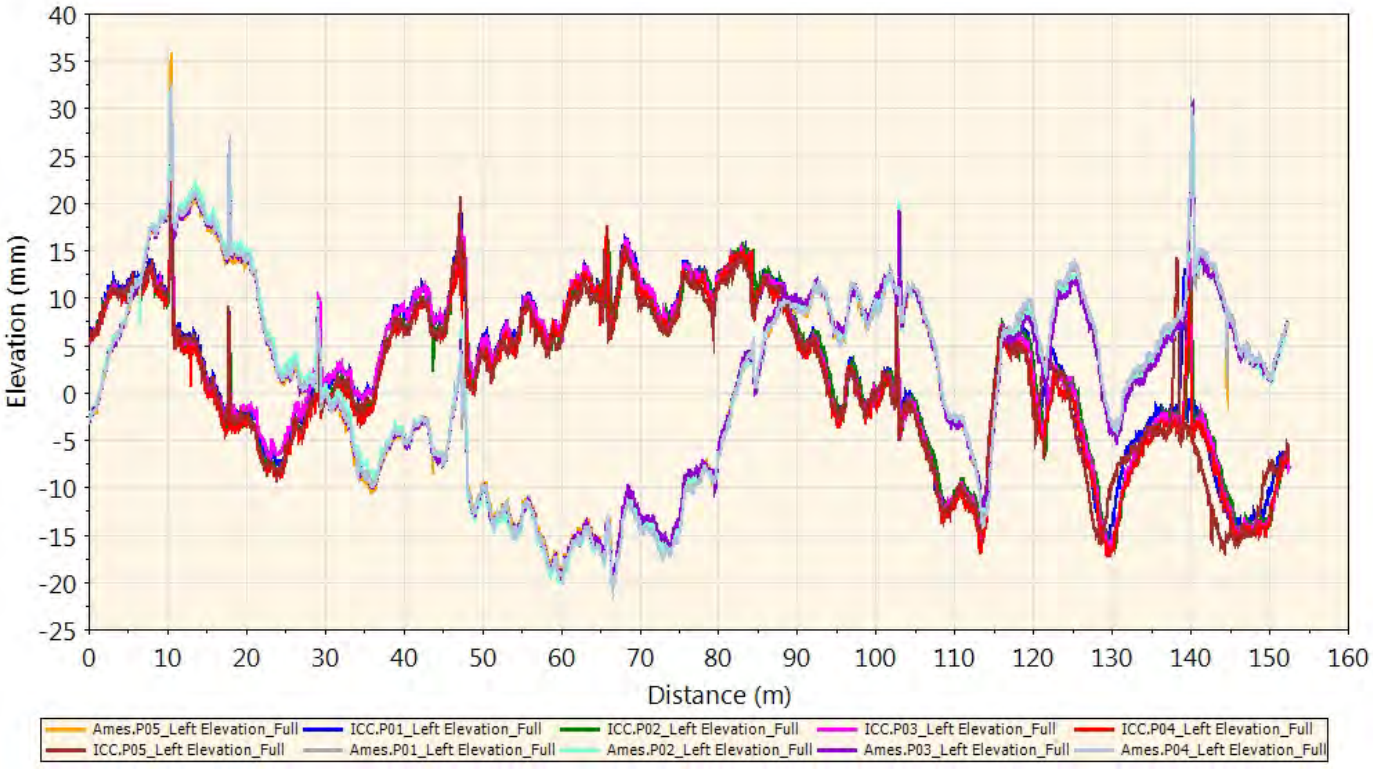

Figure 4.7. North Region, Rough PCC Section 2, 50 mph, Left Sensor

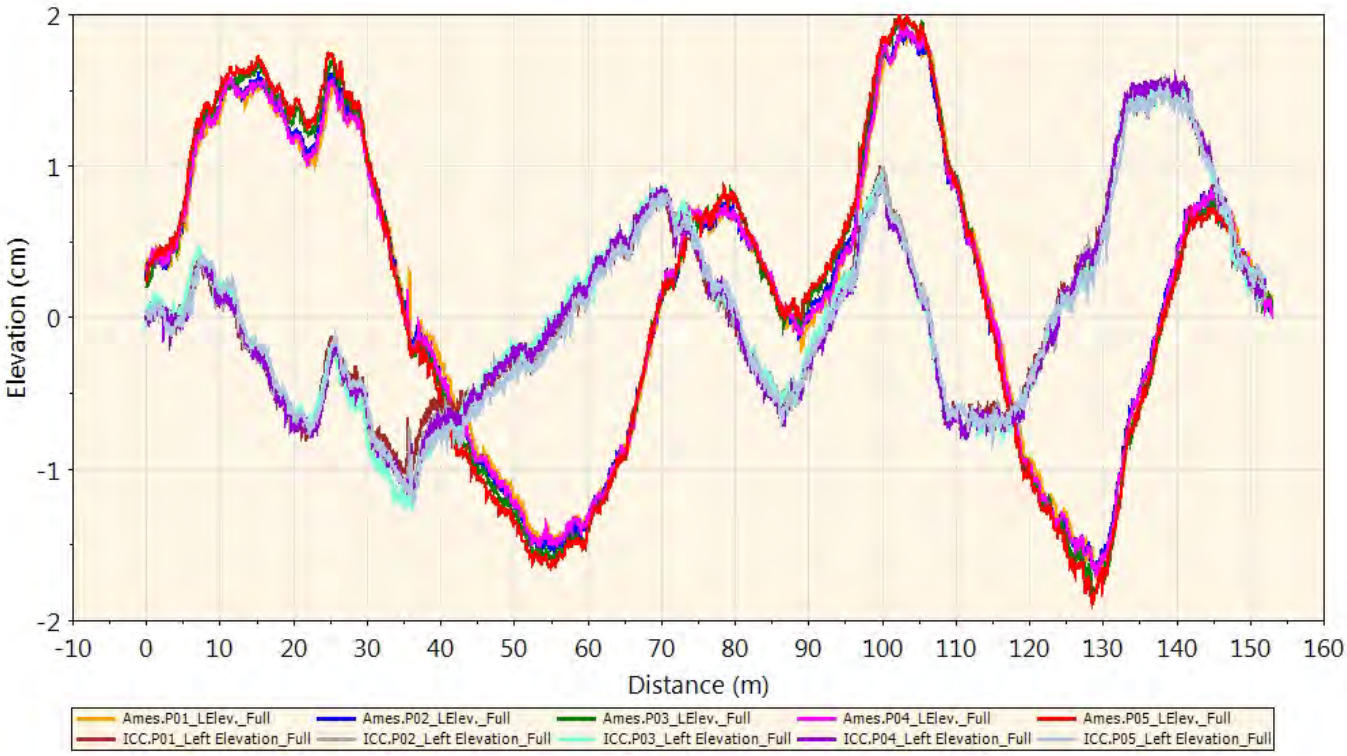

Figure 4.8. North Region, Texas Acceptance Section 1, Left Sensor

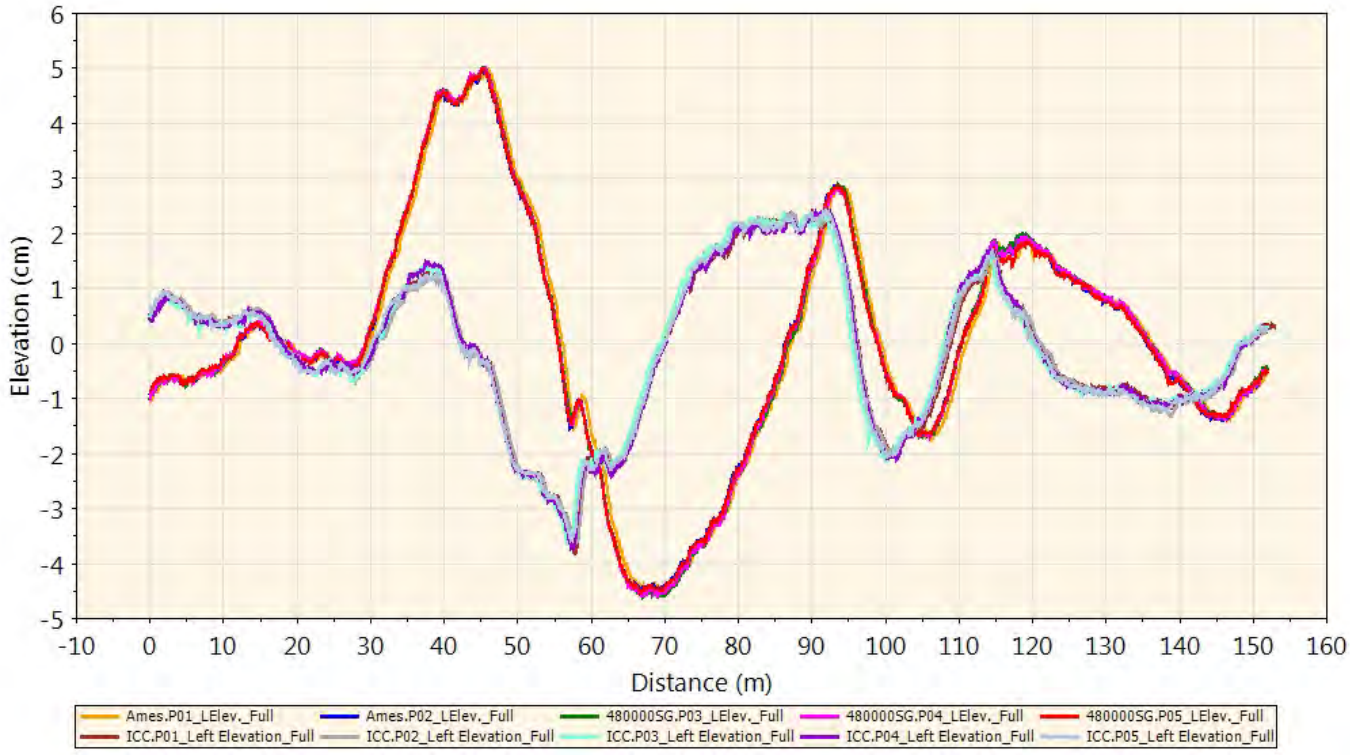

Figure 4.9. North Region, Texas Acceptance Section 2, Left Sensor

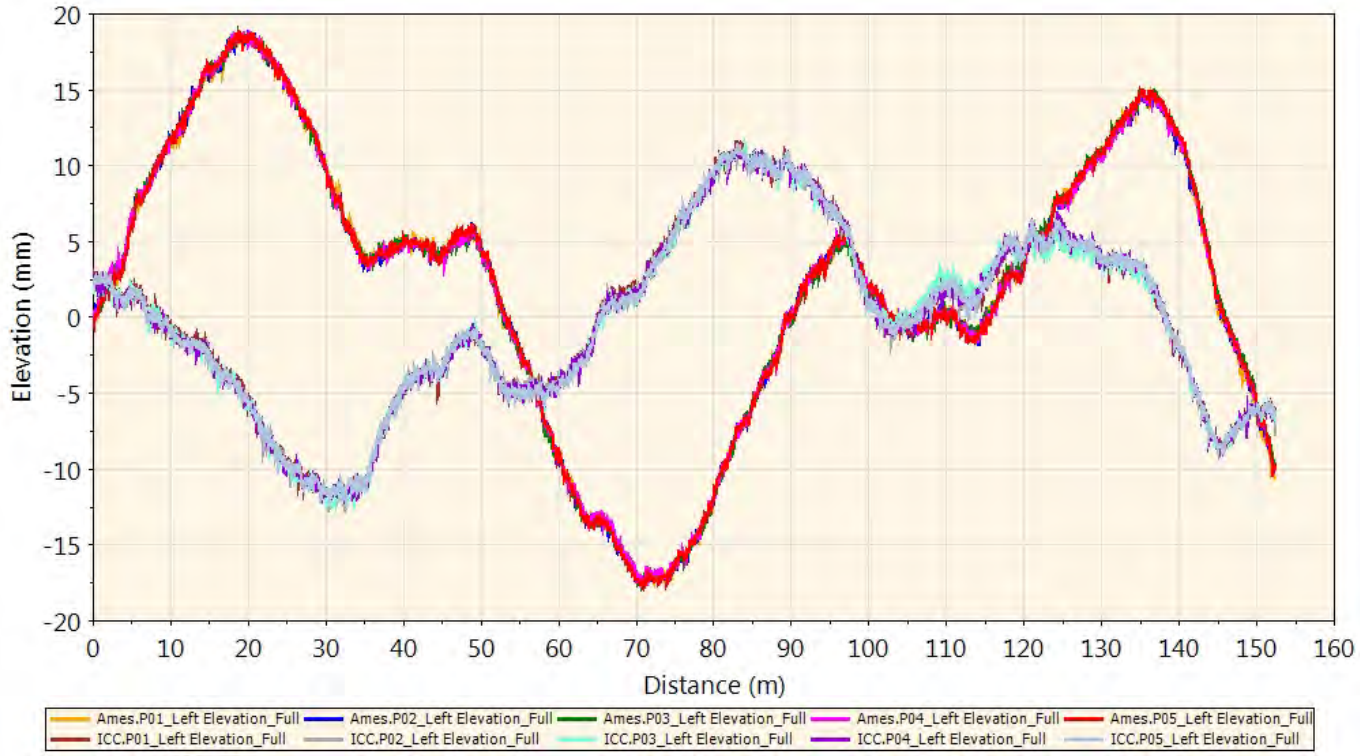

Figure 4.10. Western Region, Smooth AC, 35 mph, Left Sensor

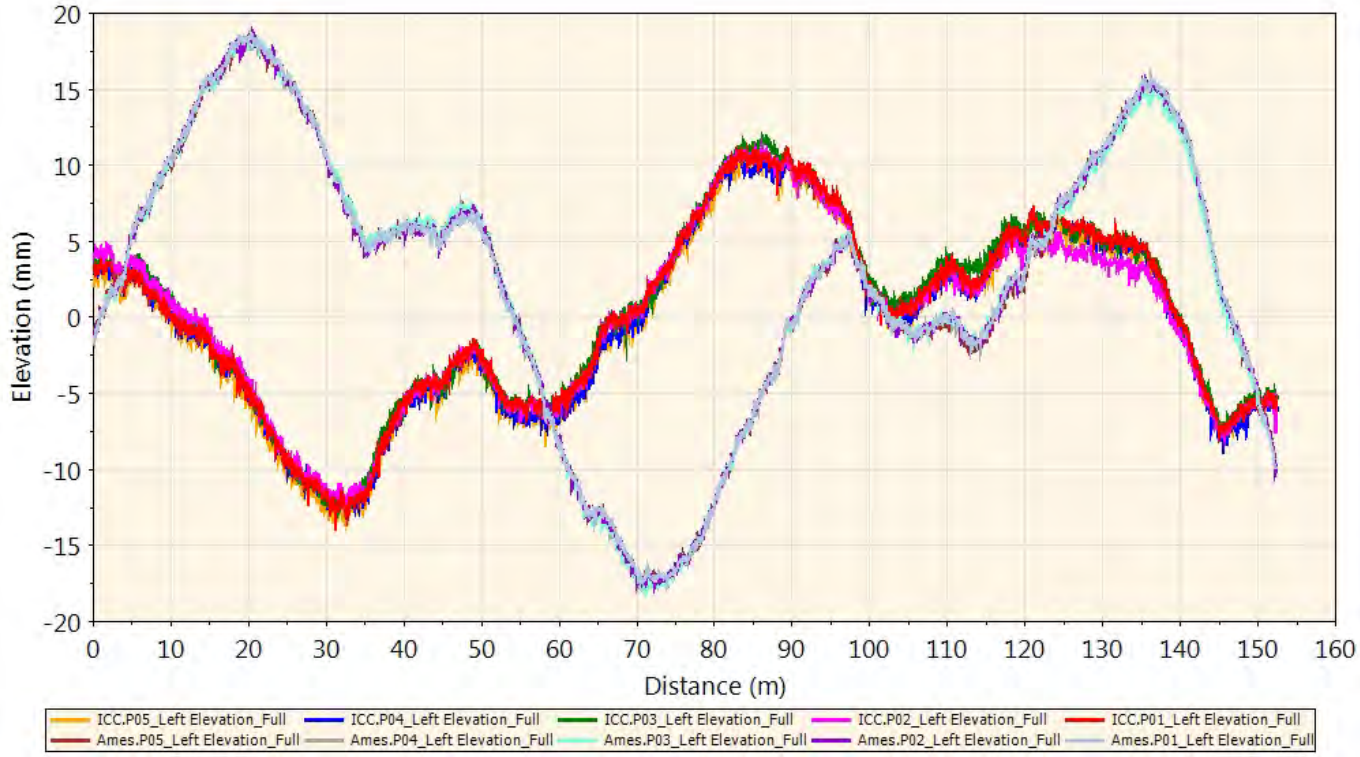

Figure 4.11. Western Region, Smooth AC, 50 mph, Left Sensor

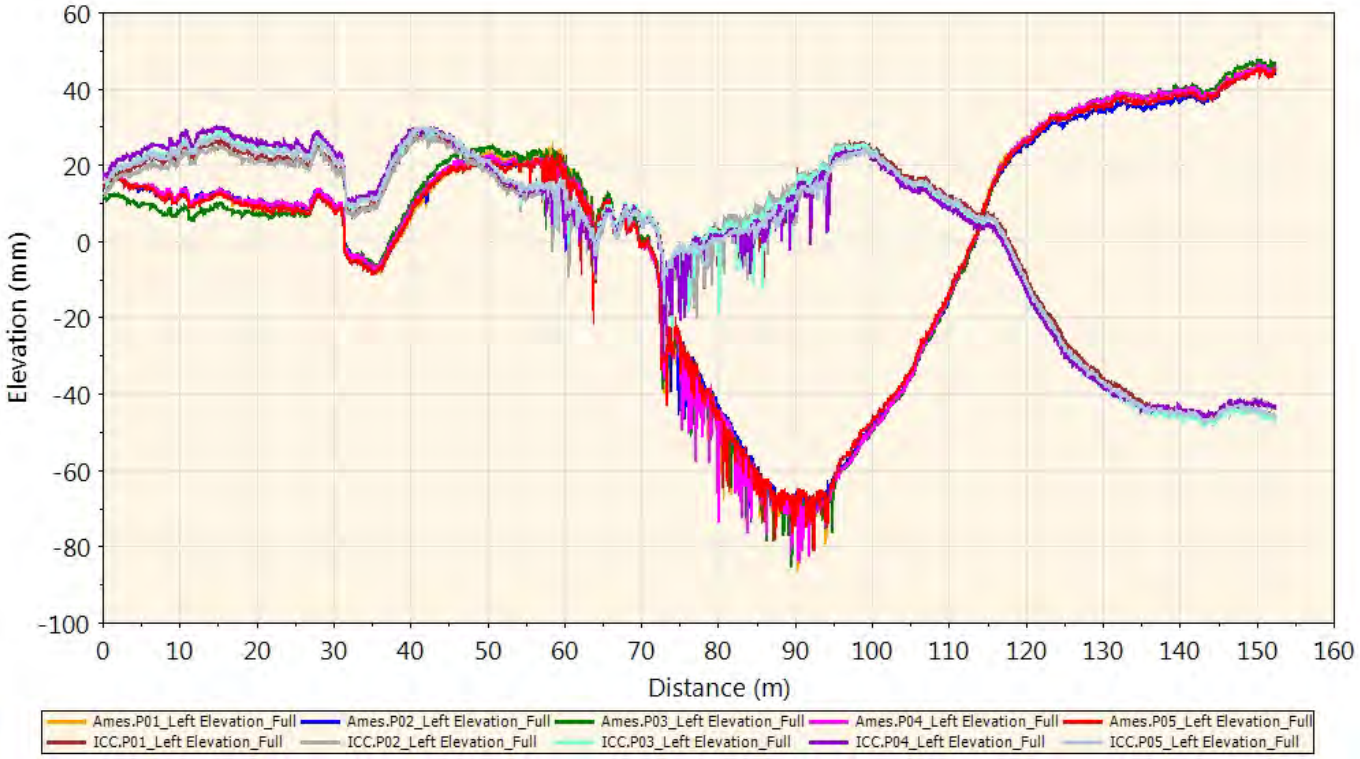

Figure 4.12. Western Region, Rough AC, 35 mph, Left Sensor

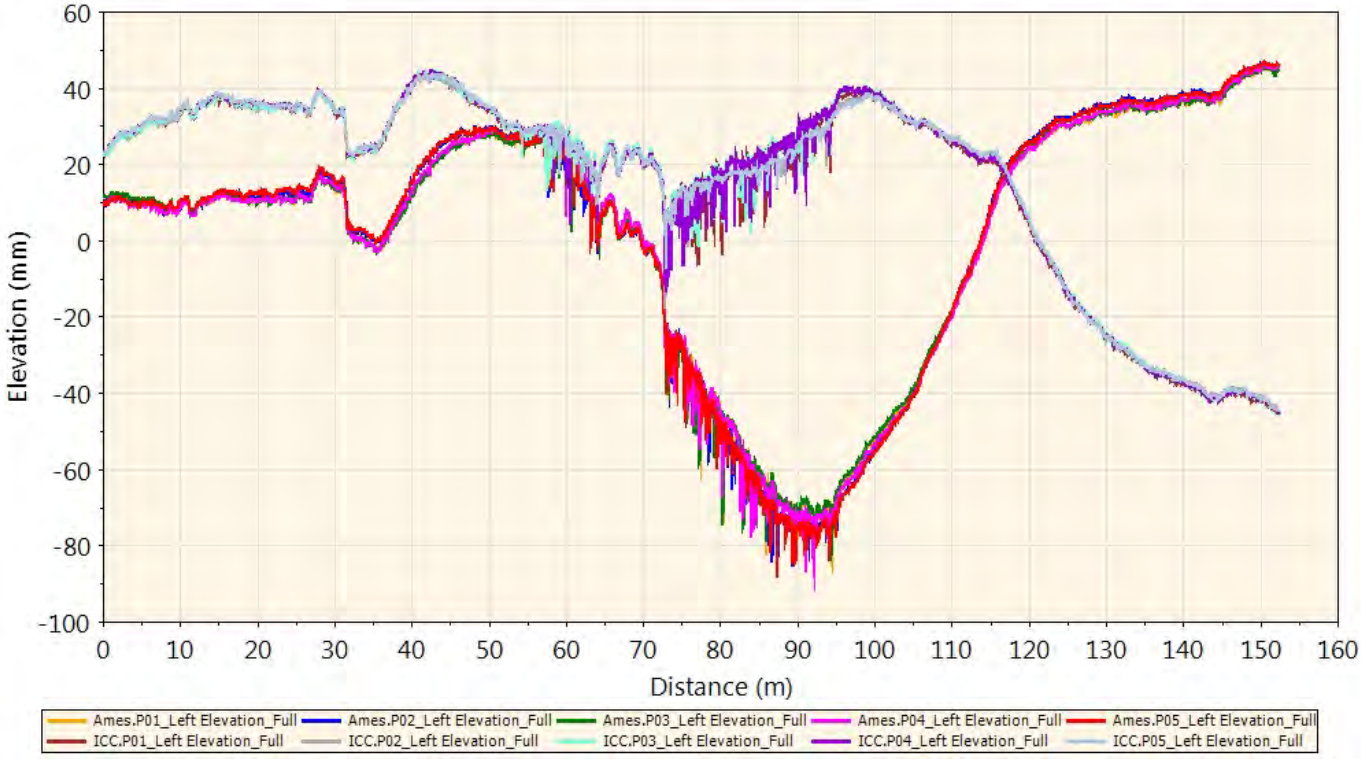

Figure 4.13. Western Region, Rough AC, 50 mph, Left Sensor

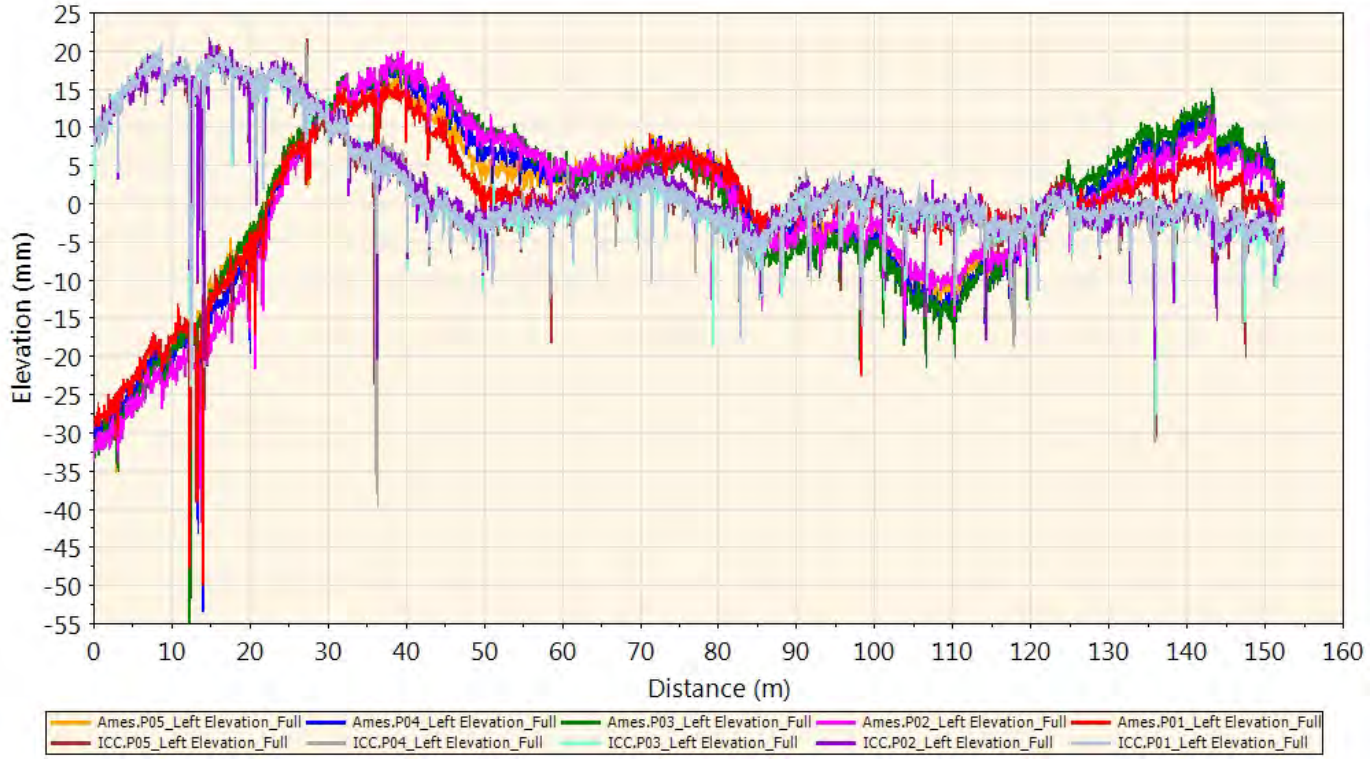

Figure 4.14. Western Region, Rough PCC, 50 mph, Left Sensor

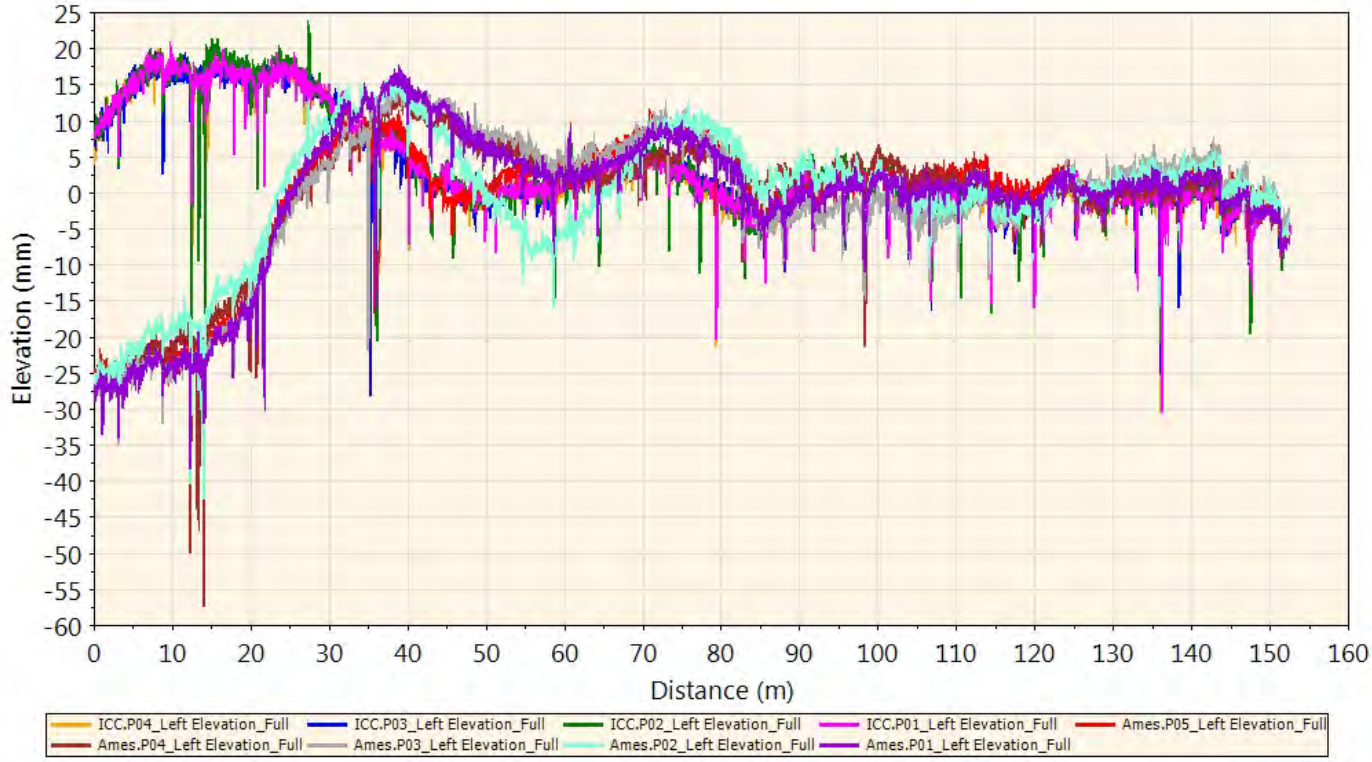

Figure 4.15. Western Region, Rough PCC, 65 mph, Left Sensor

It is known that the upper wavelength cutoff filters used by the manufacturers are not the same. The Ames units use a fourth order Butterworth filter and the ICC units use a cotangent filter. It is obvious that the units produce different raw profile elevaton data from these graphs, but based on the graphs it is not possible to identify the impacts of these differences to the IRI produced from the data.

The obvious observations from these graphs of raw elevations that will be stored in the LTPP database is that there is a very significant difference between the ICC profiler used between 2002 till 2013 and the new Ames profilers.

CHAPTER 5 – CONTINUOUS IRI

The continuous IRI is the IRI calculated at a specific segment length centered at each point in the profile. A plot of these values provides a distribution of the IRI over the section. In a comparison of the data collected by different equipment, the continuous IRI allows for a comparison of characteristics within wavelengths of greatest interest because the IRI calculation amplifies wavelengths that most impact ride quality and reduces wavelengths that do not impact ride quality.

Figures 5.1 through 5.28 present the continuous IRI for the data collected by the North and Western regions. The segment length used for these calculations is 7.62 m. The red line in each graph identifies an IRI of 1.42 m/km and is an artifact of ProVAL software which was used to create these figures.

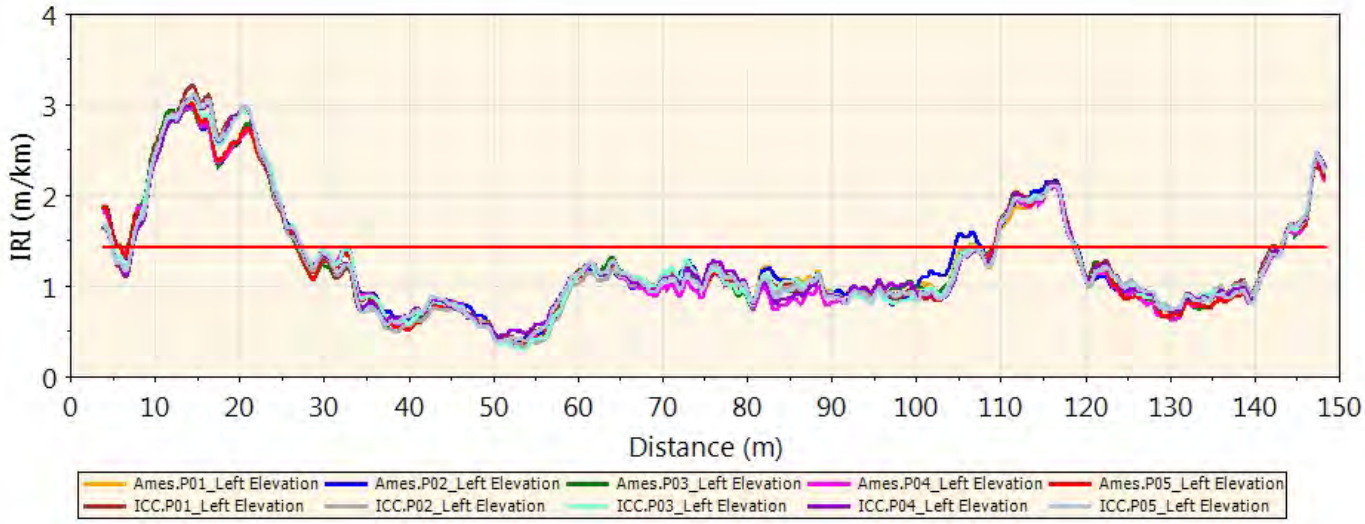

Figure 5.1. Continuous IRI for North Region, Smooth AC, 35 mph, Left Sensor, Average Difference 0.07 m/km

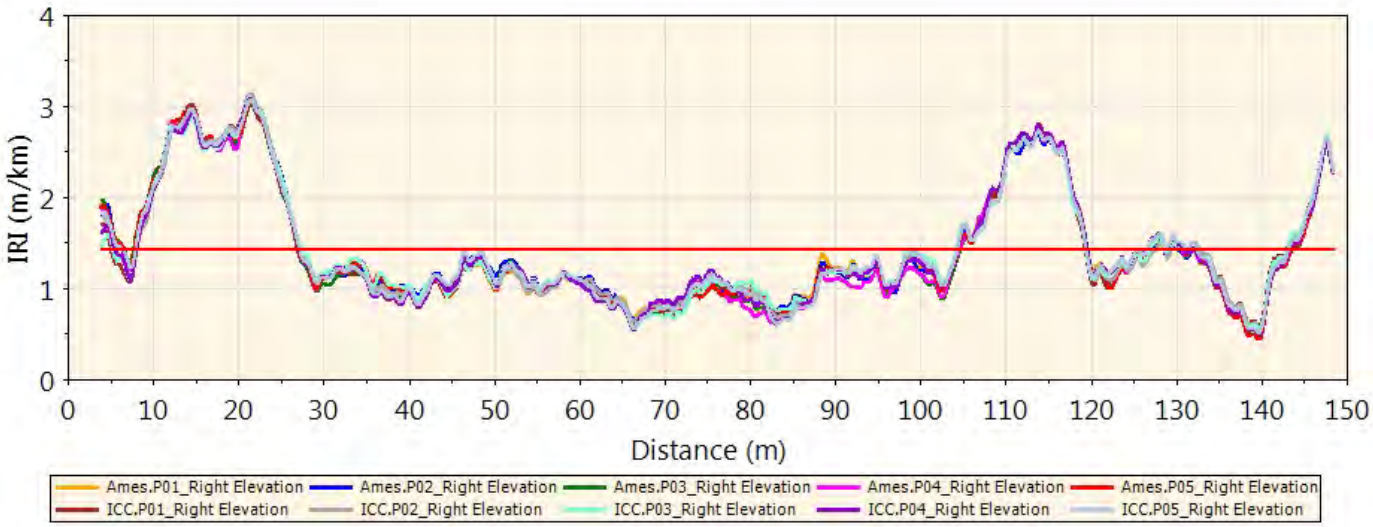

Figure 5.2. Continuous IRI for North Region, Smooth AC, 35 mph, Right Sensor, Average Difference 0.13 m/km

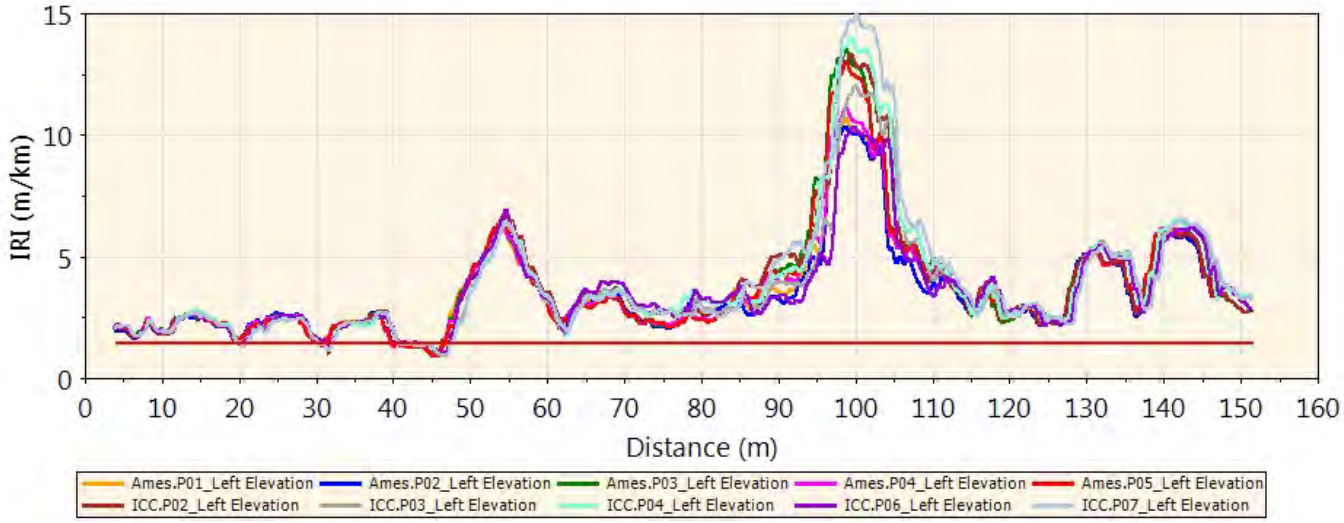

Figure 5.3. Continuous IRI for North Region, Rough AC, 35 mph, Left Sensor, Average Difference 0.69 m/km

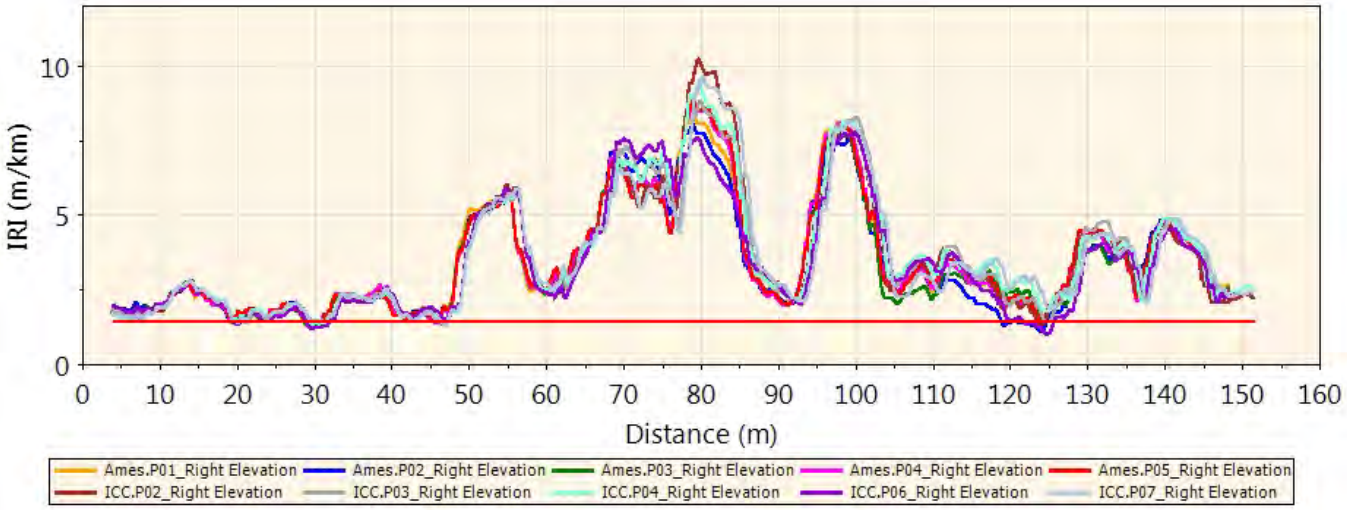

Figure 5.4. Continuous IRI for North Region, Rough AC, 35 mph, Right Sensor, Average Difference 0.21 m/km

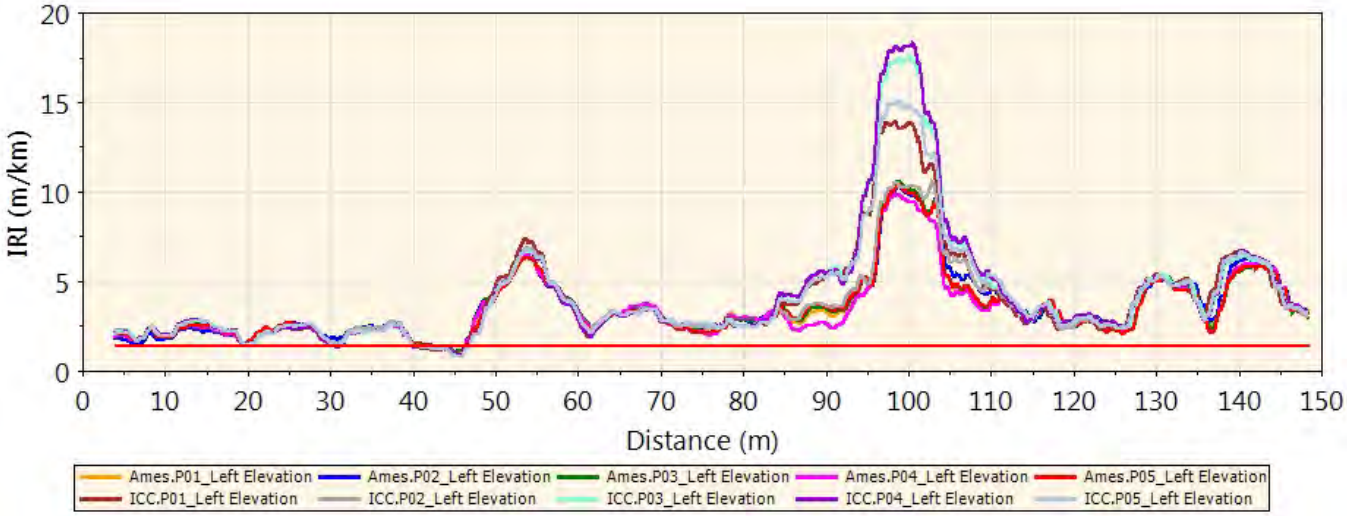

Figure 5.5. Continuous IRI for North Region, Rough AC, 50 mph, Left Sensor, Average Difference 0.83 m/km

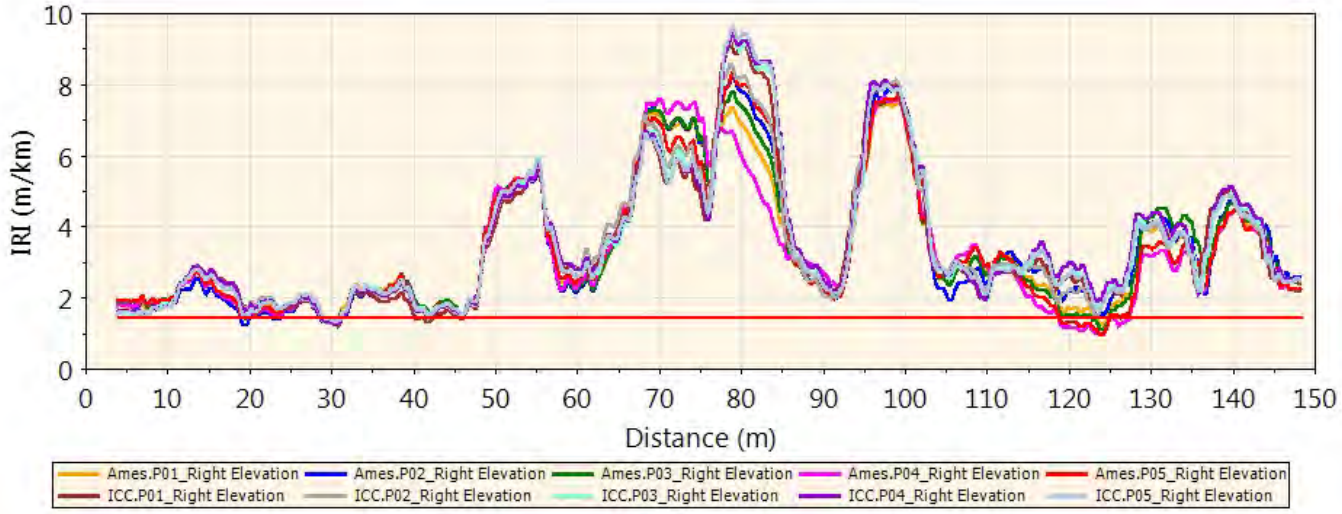

Figure 5.6. Continuous IRI for North Region, Rough AC, 50 mph, Right Sensor, Average Difference 0.34 m/km

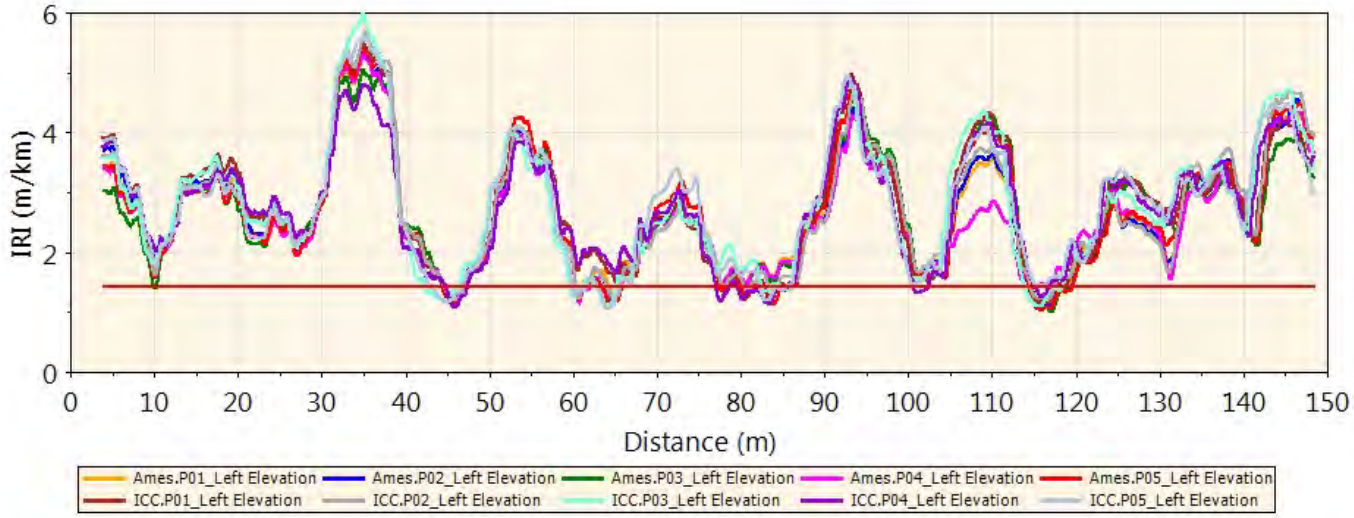

Figure 5.7. Continuous IRI for North Region, Rough PCC Section 1, 35 mph, Left Sensor, Average Difference 0.41 m/km

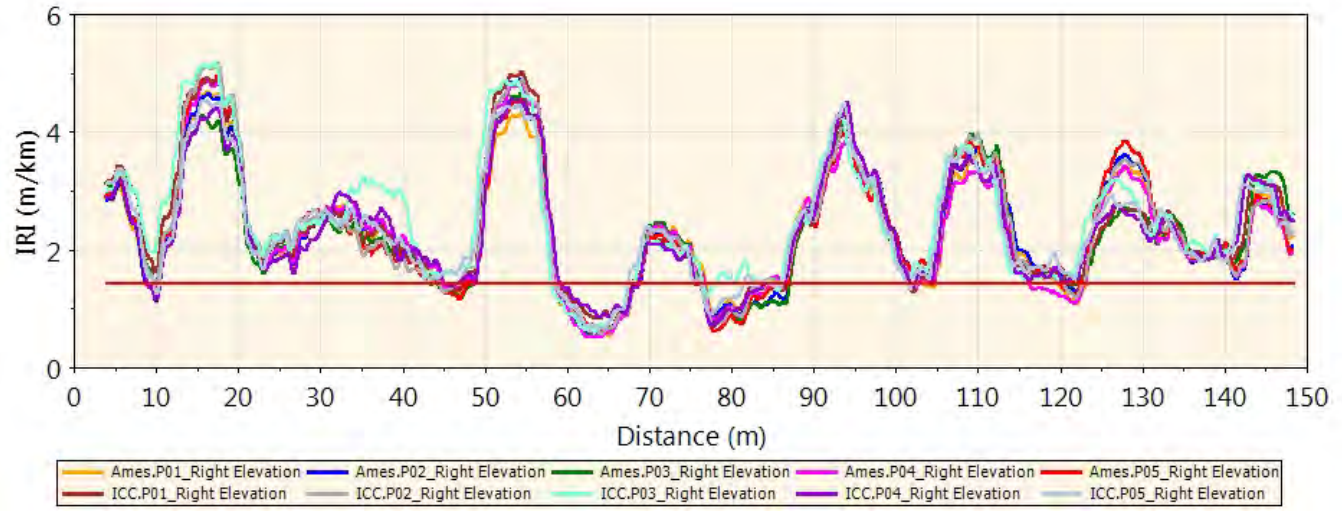

Figure 5.8. Continuous IRI for North Region, Rough PCC Section 1, 35 mph, Right Sensor, Average Difference 0.05 m/km

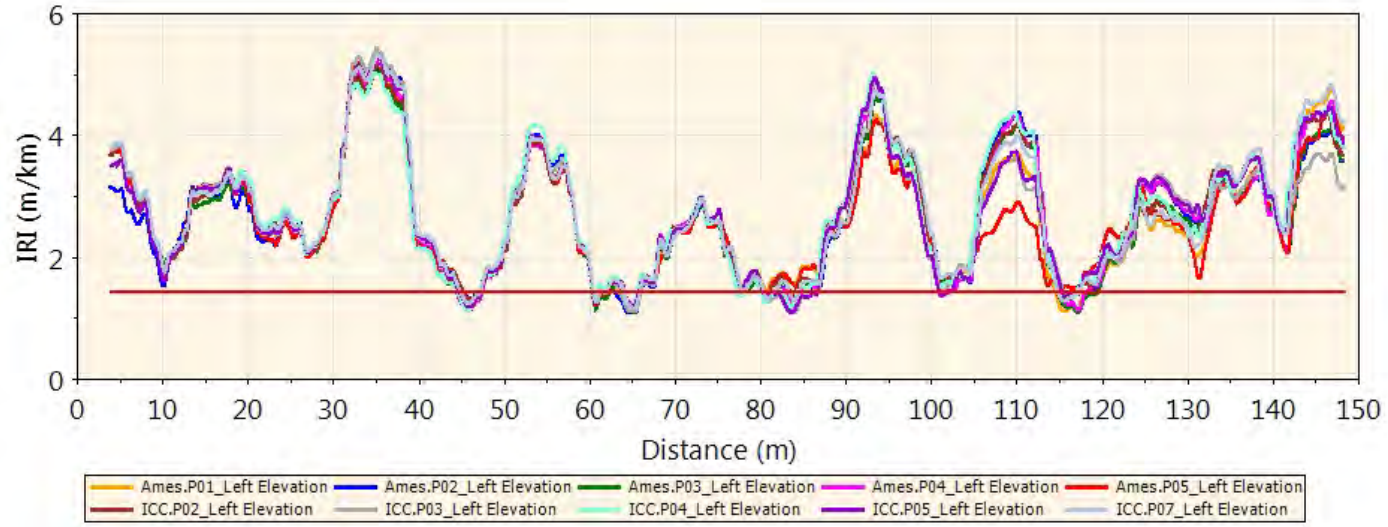

Figure 5.9. Continuous IRI for North Region, Rough PCC Section 1, 50 mph, Left Sensor, Average Difference 0.31 m/km

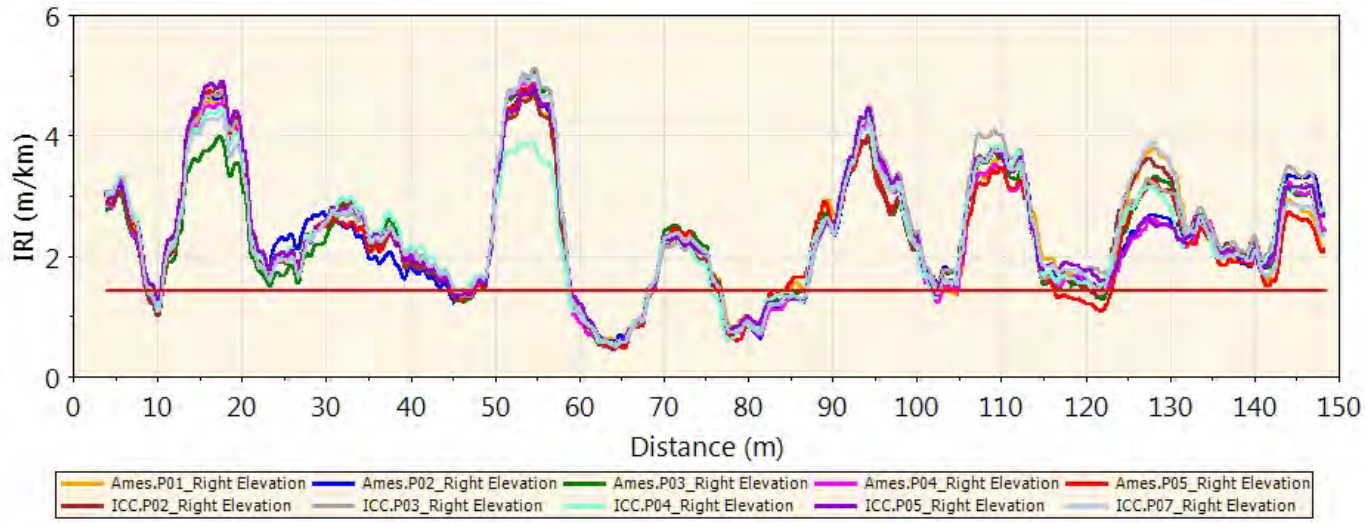

Figure 5.10. Continuous IRI for North Region, Rough PCC Section 1, 50 mph, Right Sensor, Average Difference 0.10 m/km

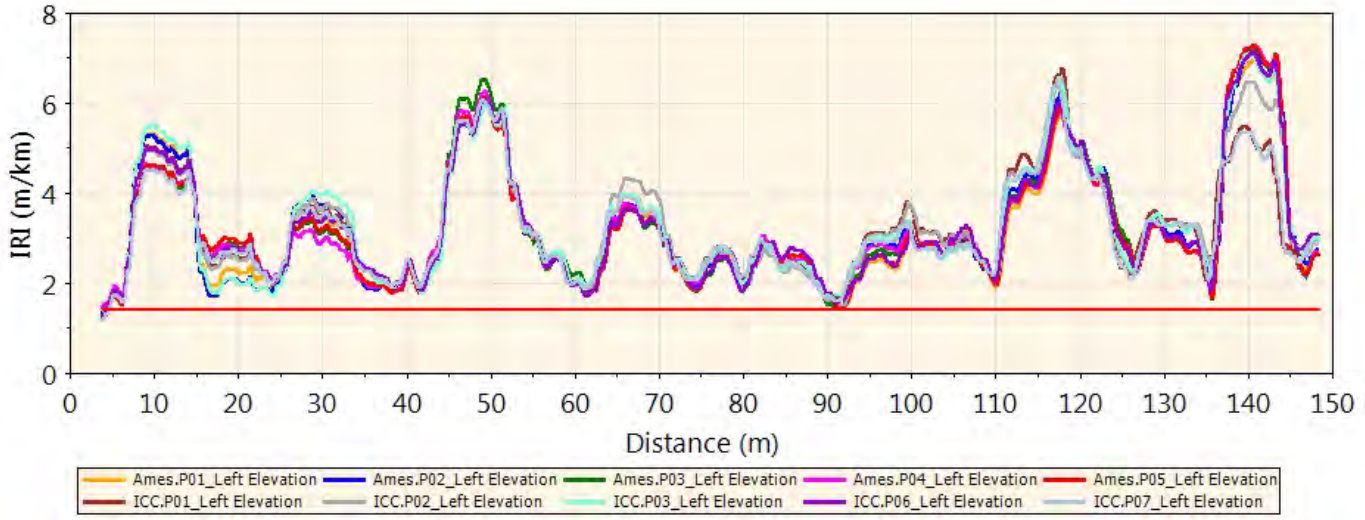

Figure 5.11. Continuous IRI for North Region, Rough PCC Section 2, 35 mph, Left Sensor, Average Difference 0.32 m/km

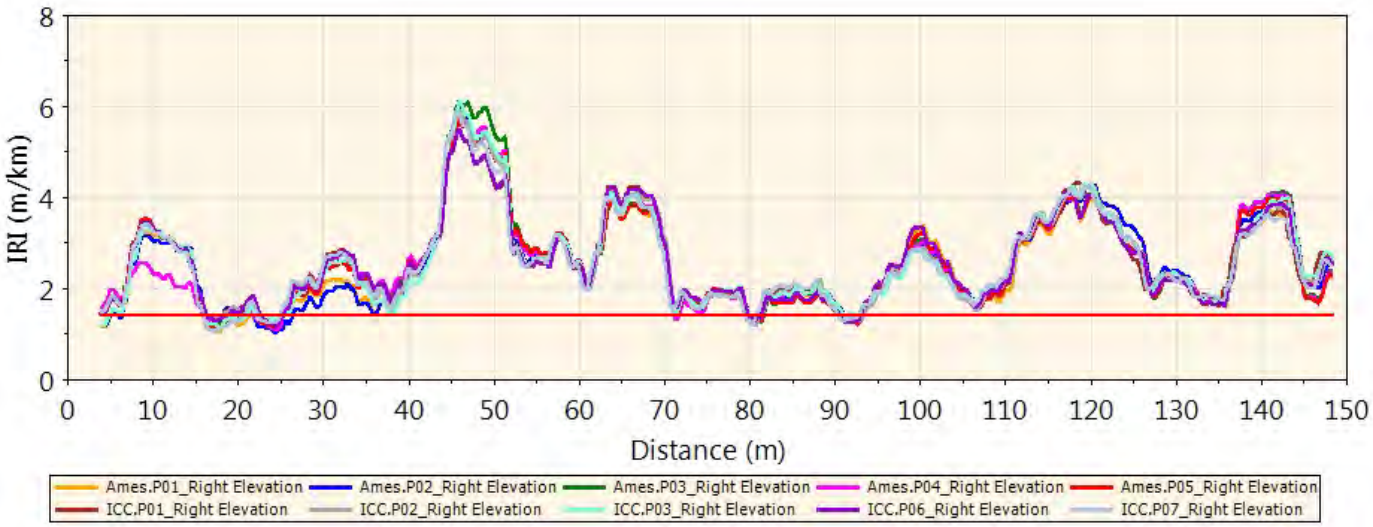

Figure 5.12. Continuous IRI for North Region, Rough PCC Section 2, 35 mph, Right Sensor, Average Difference 0.24 m/km

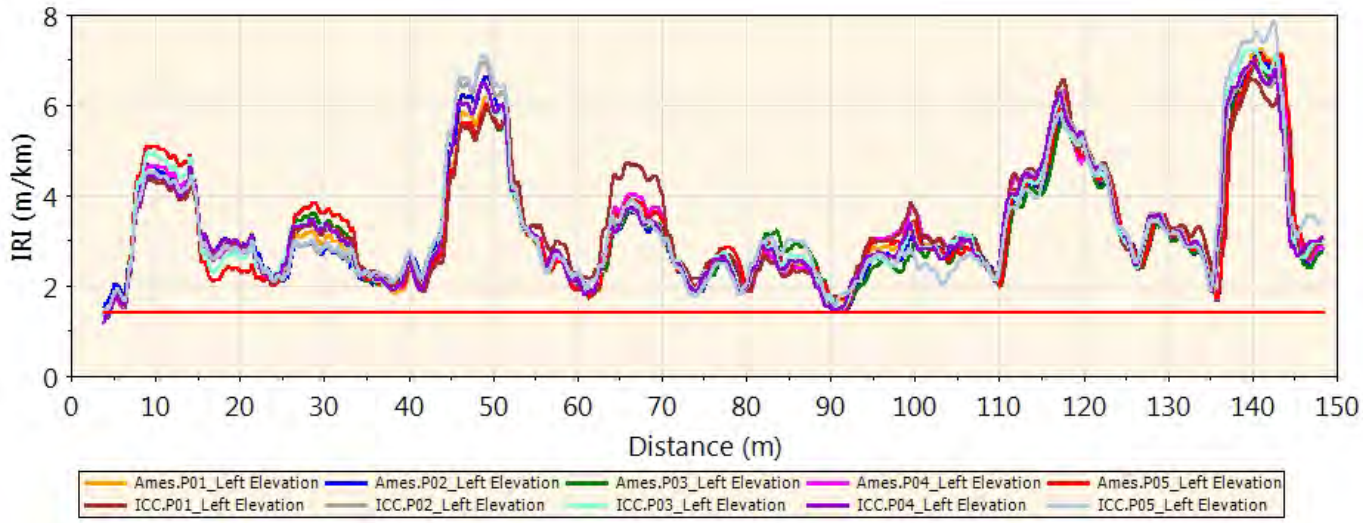

Figure 5.13. Continuous IRI for North Region, Rough PCC Section 2, 50 mph, Left Sensor, Average Difference 0.29 m/km

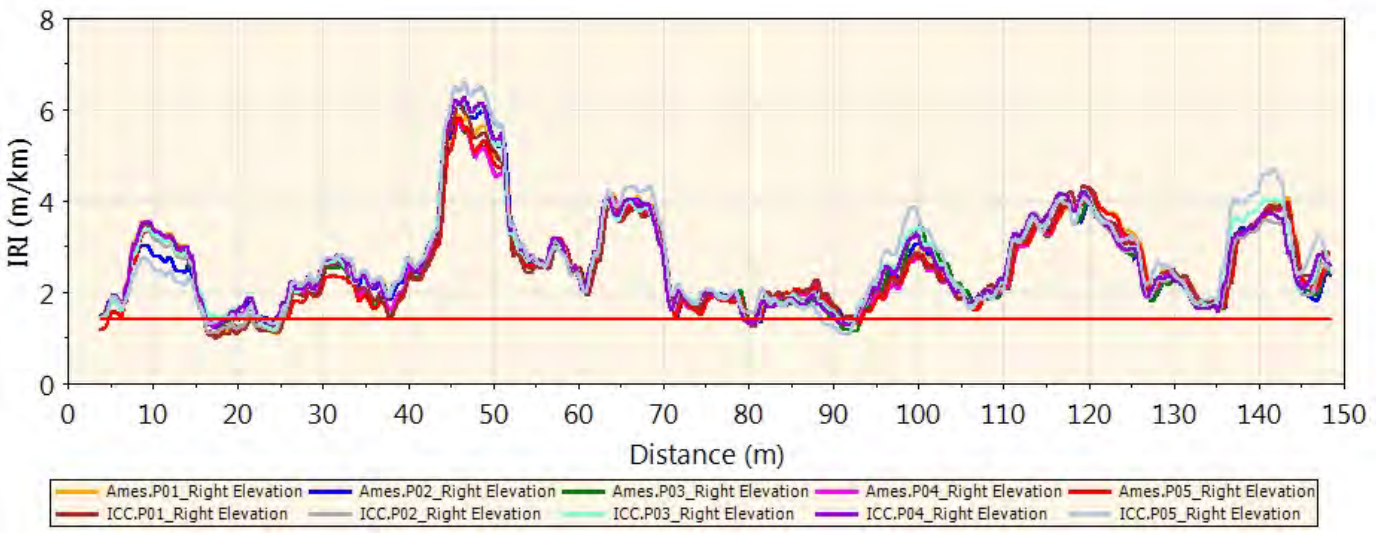

Figure 5.14. Continuous IRI for North Region, Rough PCC Section 2, 50 mph, Right Sensor, Average Difference 0.23 m/km

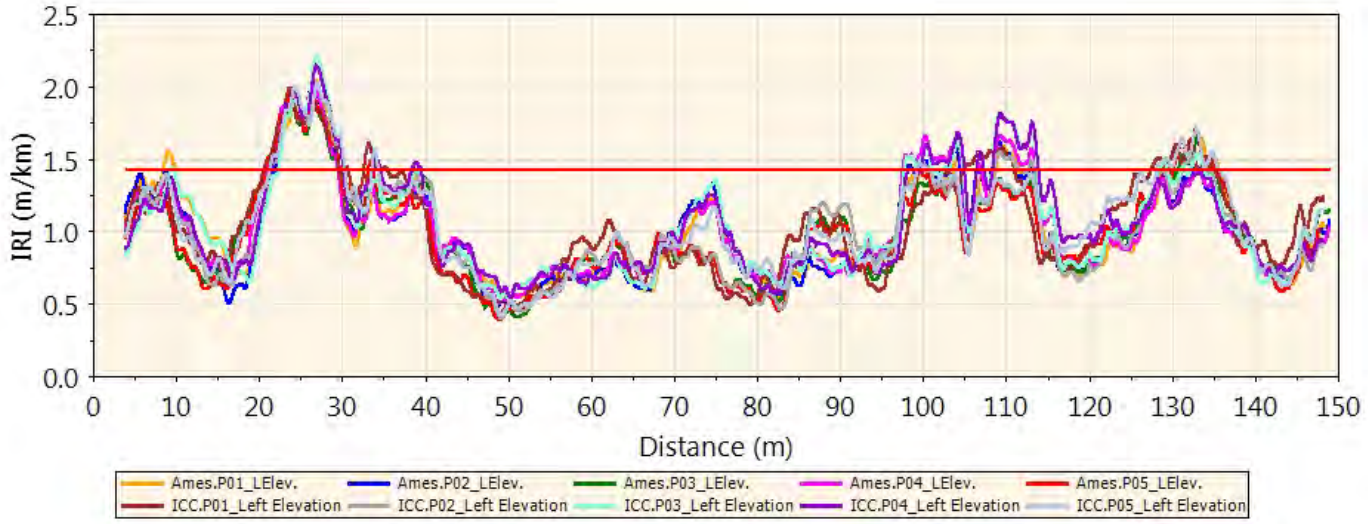

Figure 5.15. Continuous IRI for North Region, Texas Acceptance Section 1, 50 mph, Left Sensor, Average Difference 0.02 m/km

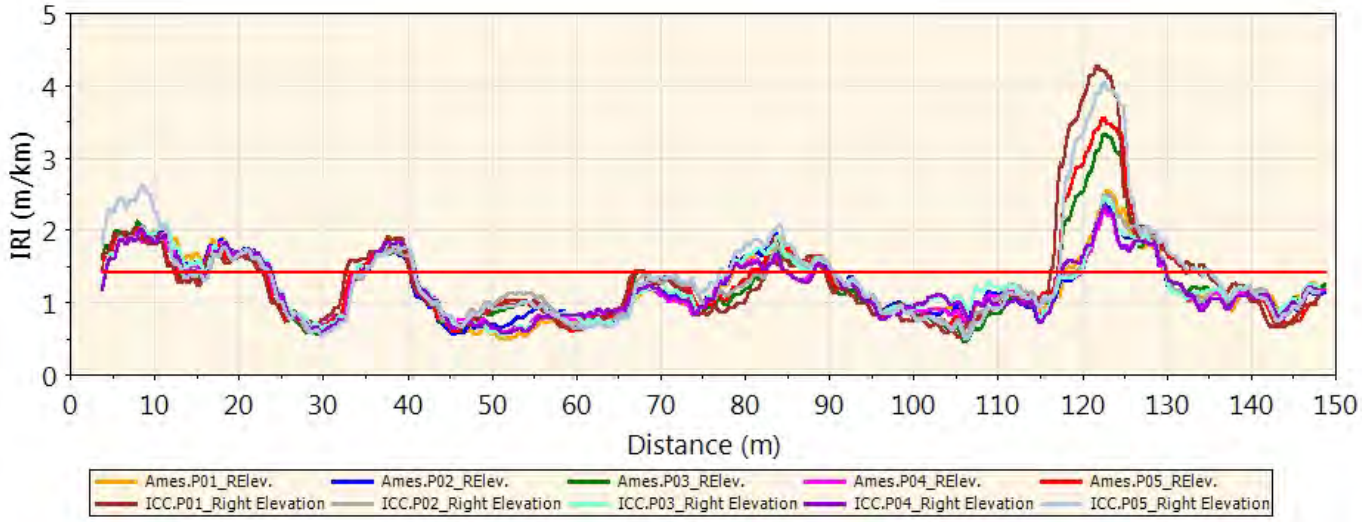

Figure 5.16. Continuous IRI for North Region, Texas Acceptance Section 1, 50 mph, Right Sensor, Average Difference 0.02 m/km

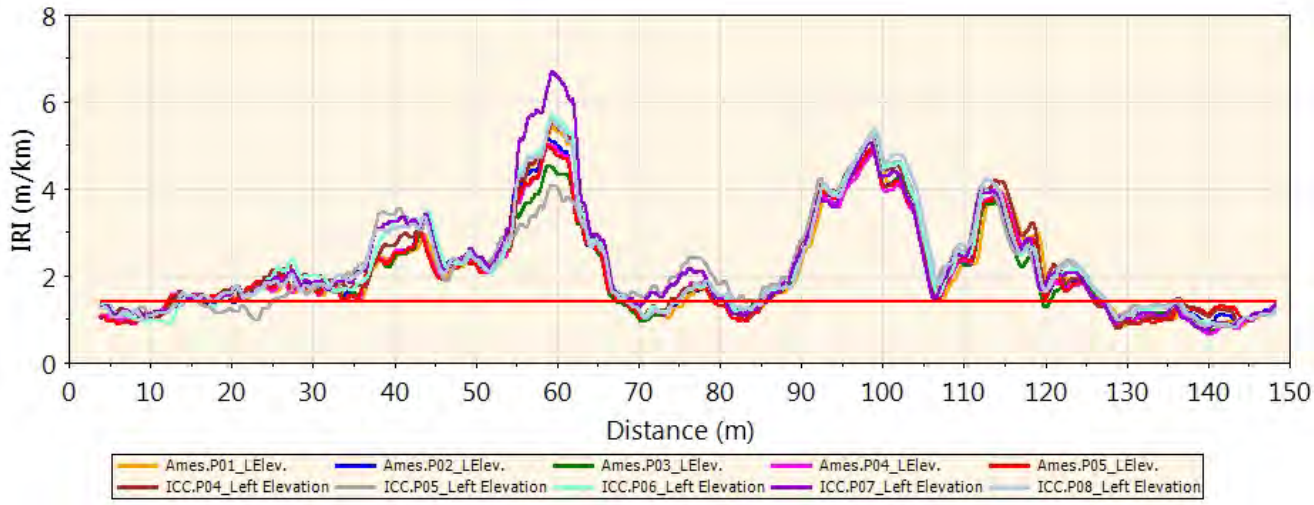

Figure 5.17. Continuous IRI for North Region, Texas Acceptance Section 2, 50 mph, Left Sensor, Average Difference 0.14 m/km

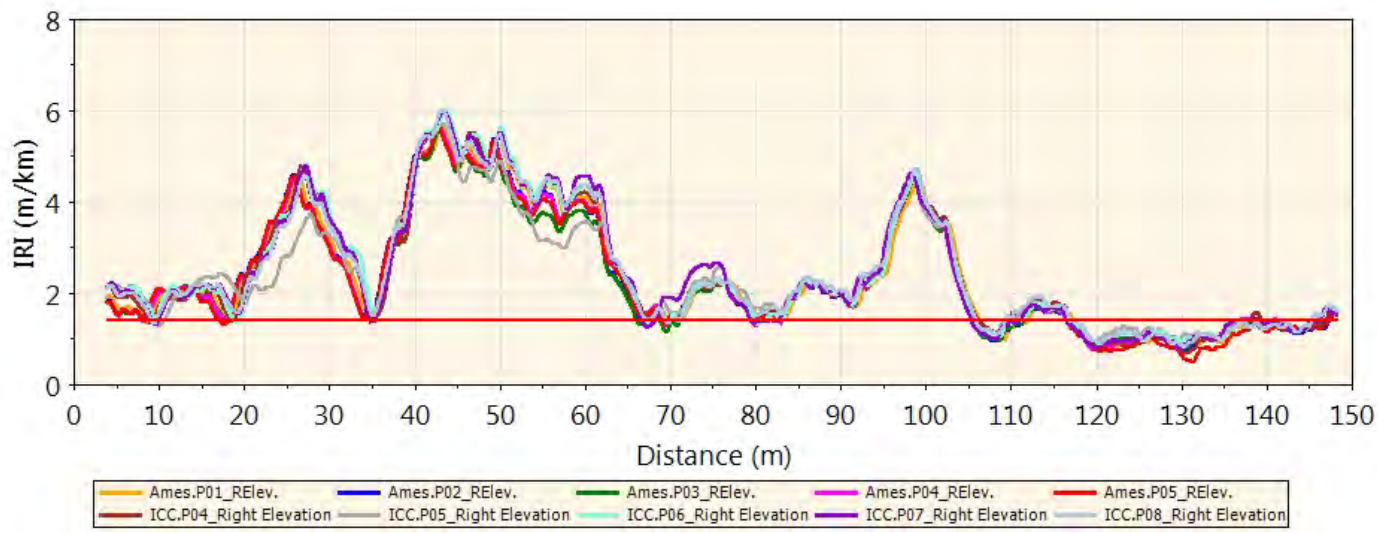

Figure 5.18. Continuous IRI for North Region, Texas Acceptance Section 2, 50 mph, Right Sensor, Average Difference 0.09 m/km

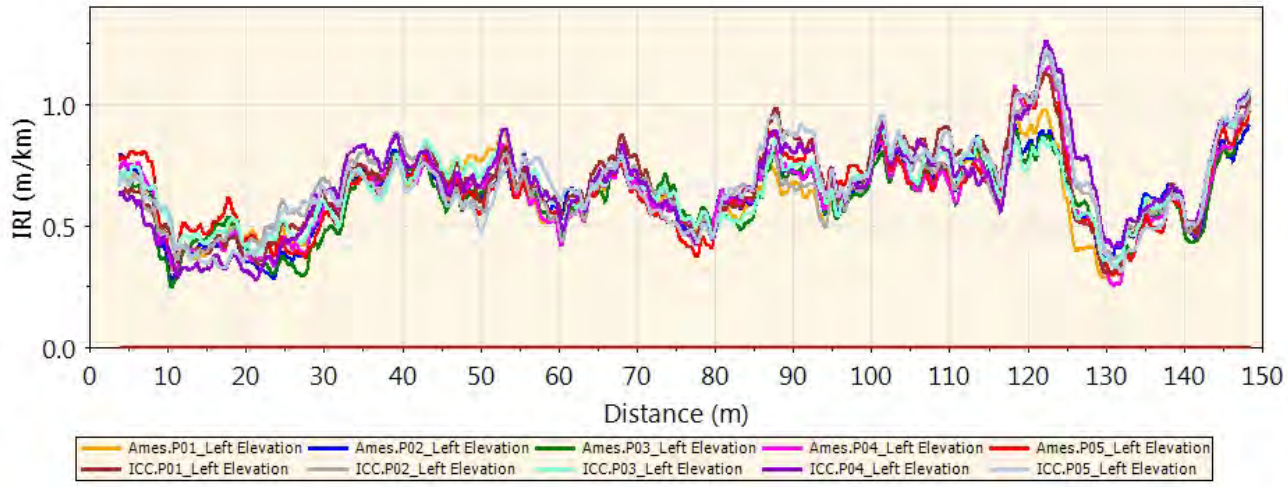

Figure 5.19. Continuous IRI for Western Region, Smooth AC, 35 mph, Left Sensor, Average Difference 0.04 m/km

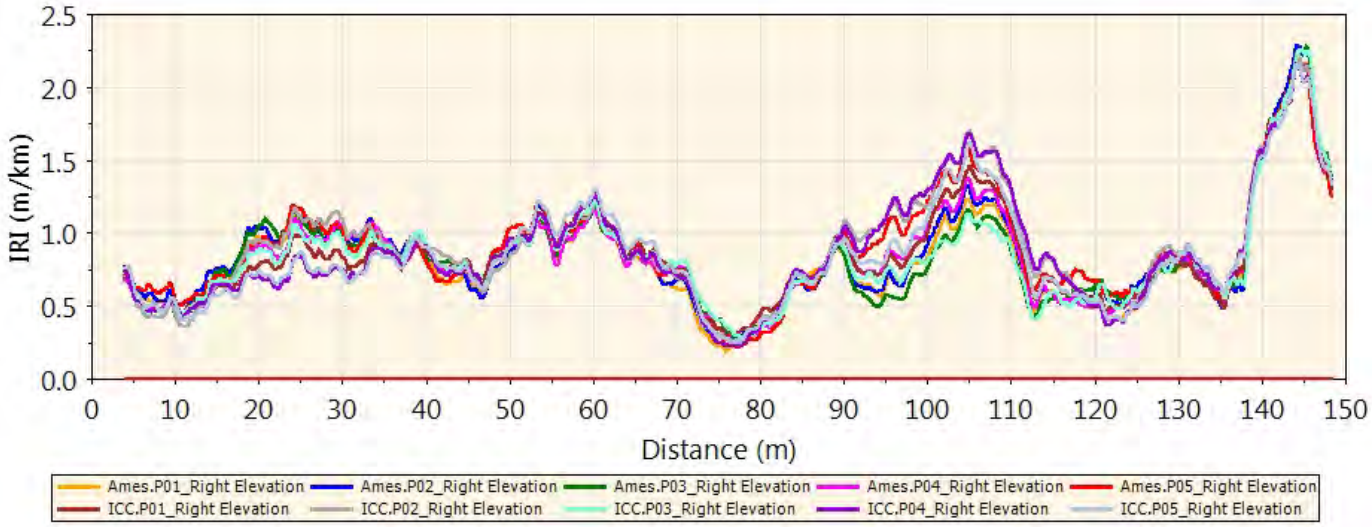

Figure 5.20. Continuous IRI for Western Region, Smooth AC, 35 mph, Right Sensor, Average Difference 0.01 m/km

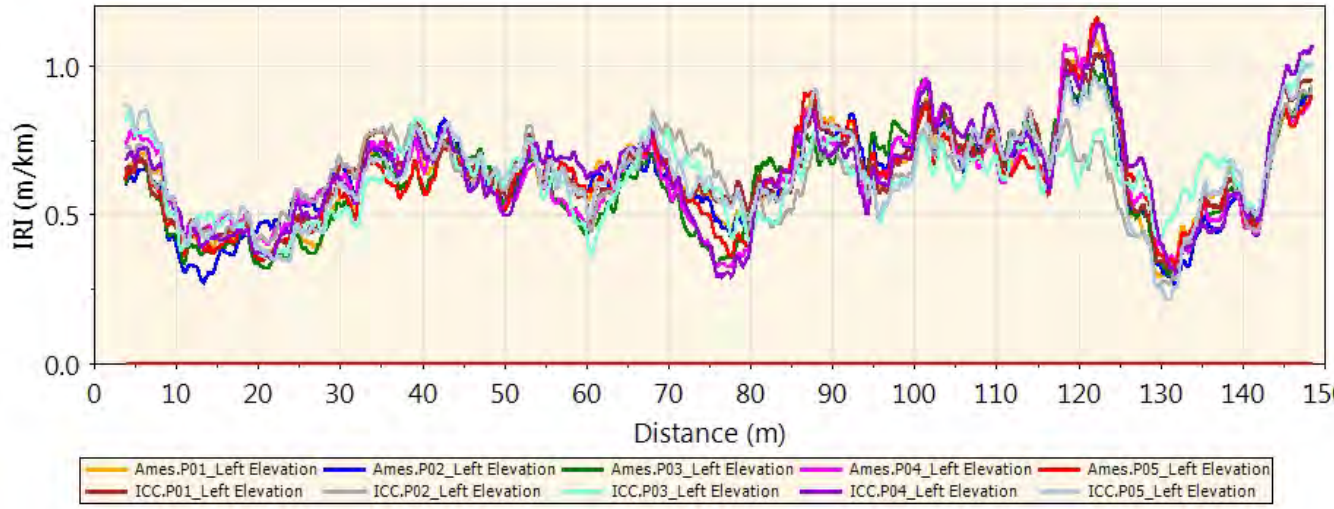

Figure 5.21. Continuous IRI for Western Region, Smooth AC, 50 mph, Left Sensor, Average Difference 0.01 m/km

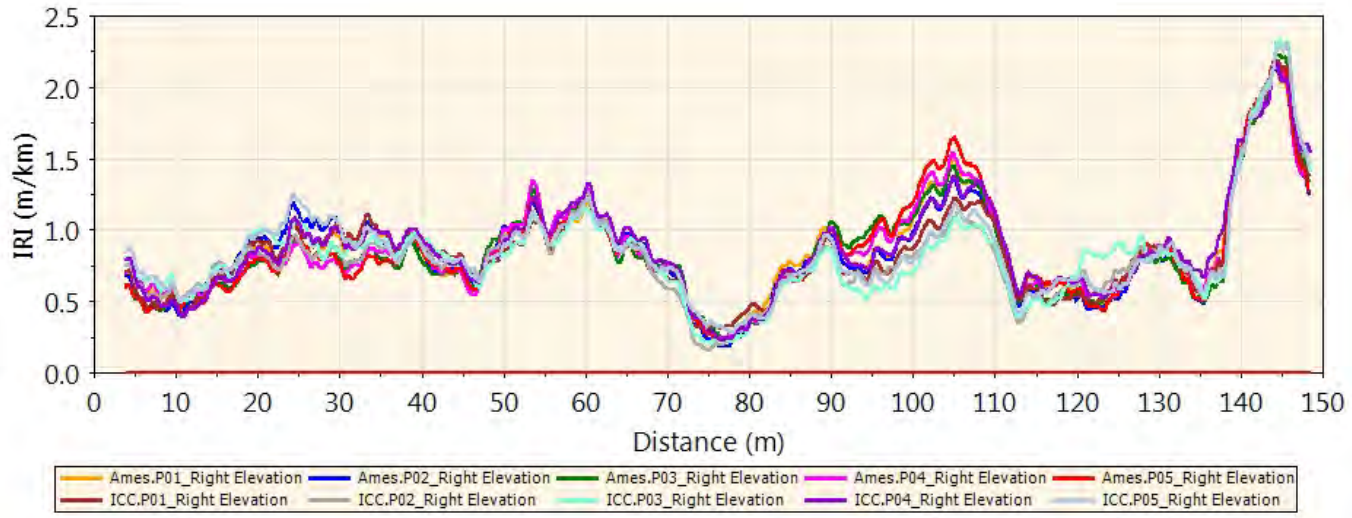

Figure 5.22. Continuous IRI for Western Region, Smooth AC, 50 mph, Right Sensor, Average Difference 0.00 m/km

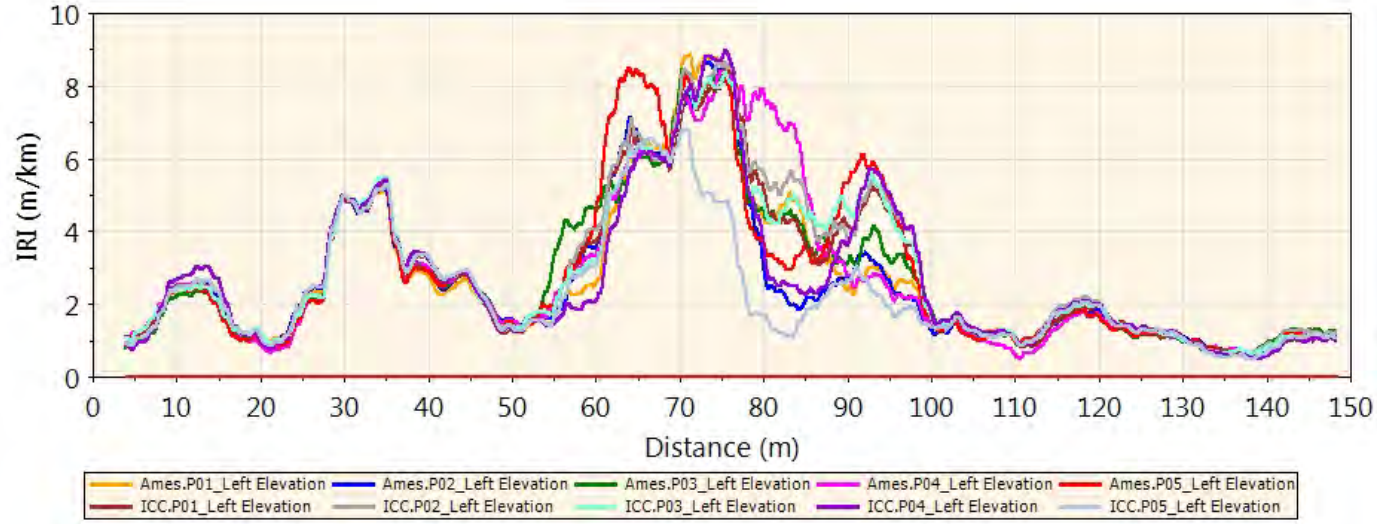

Figure 5.23. Continuous IRI for Western Region, Rough AC, 35 mph, Left Sensor, Average Difference 0.11 m/km

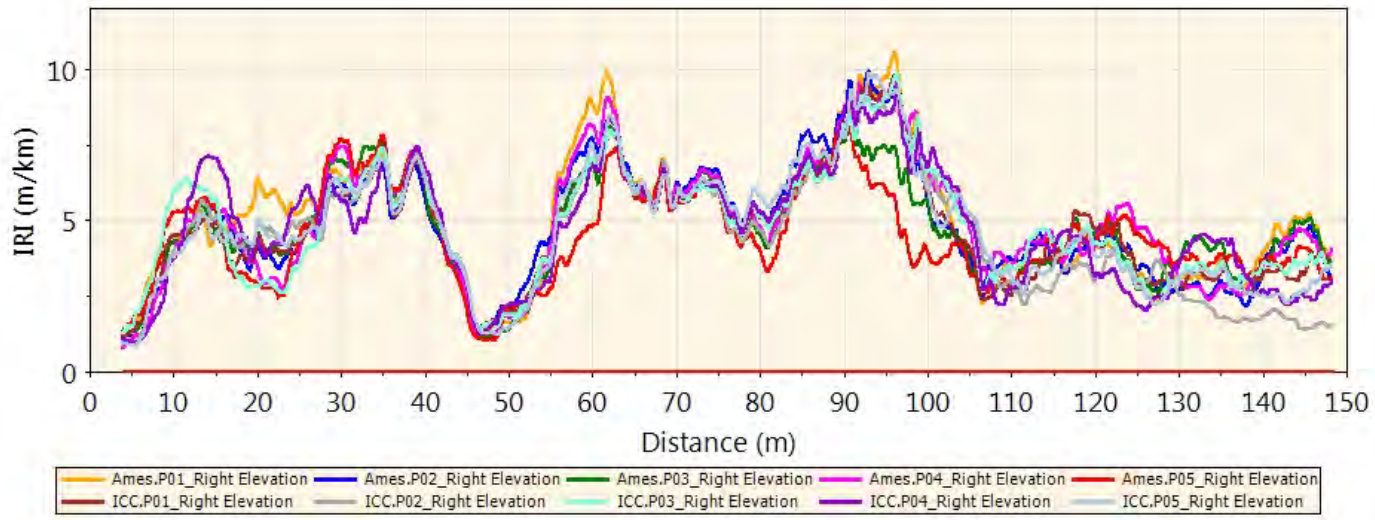

Figure 5.24. Continuous IRI for Western Region, Rough AC, 35 mph, Right Sensor, Average Difference 0.19 m/km

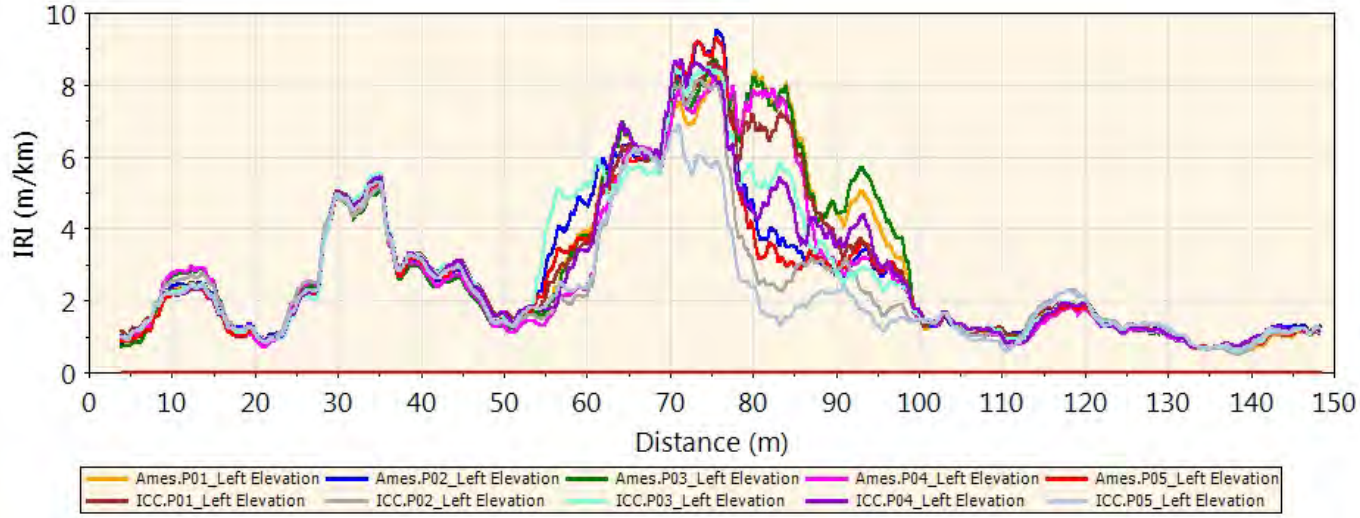

Figure 5.25. Continuous IRI for Western Region, Rough AC, 50 mph, Left Sensor, Average Difference 0.05 m/km

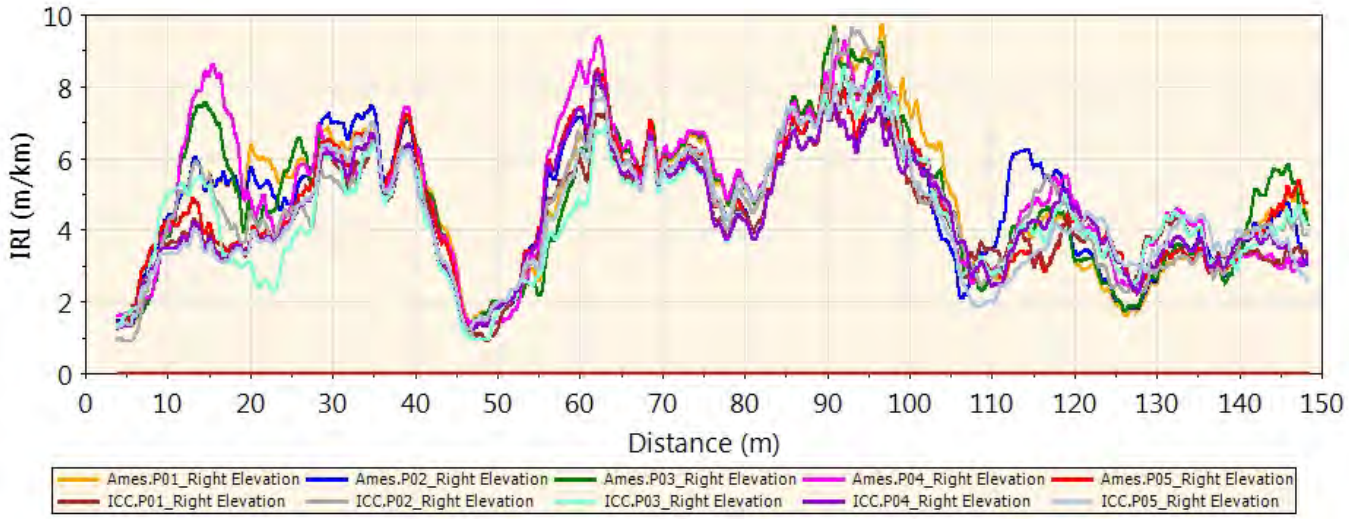

Figure 5.26. Continuous IRI for Western Region, Rough AC, 50 mph, Right Sensor, Average Difference 0.30 m/km

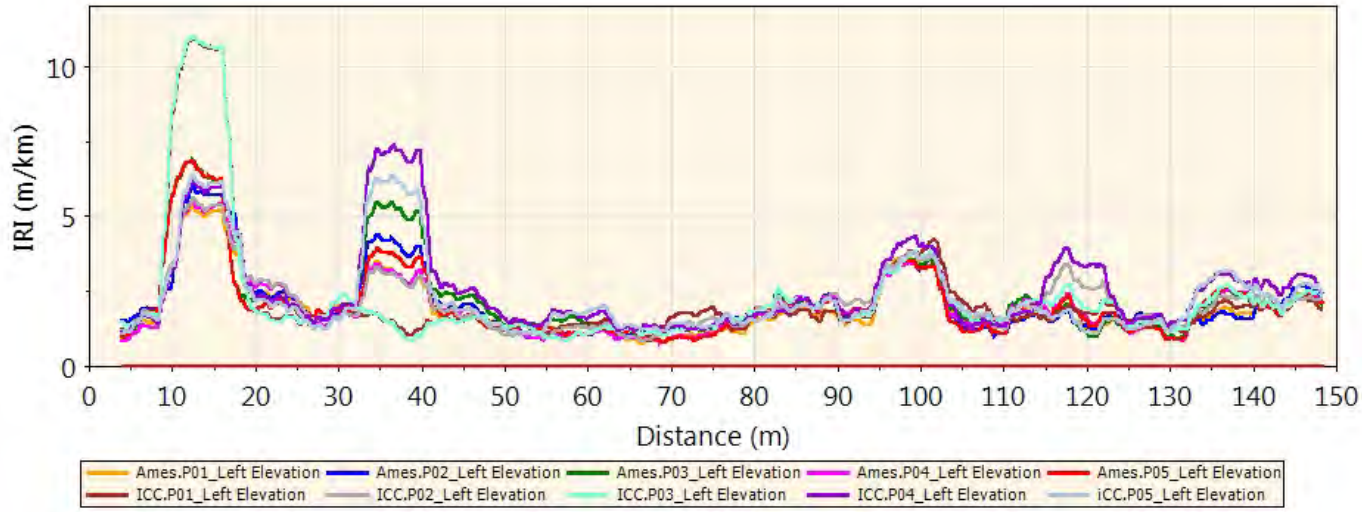

Figure 5.27. Continuous IRI for Western Region, Rough PCC, 50 mph, Left Sensor, Average Difference 0.23 m/km

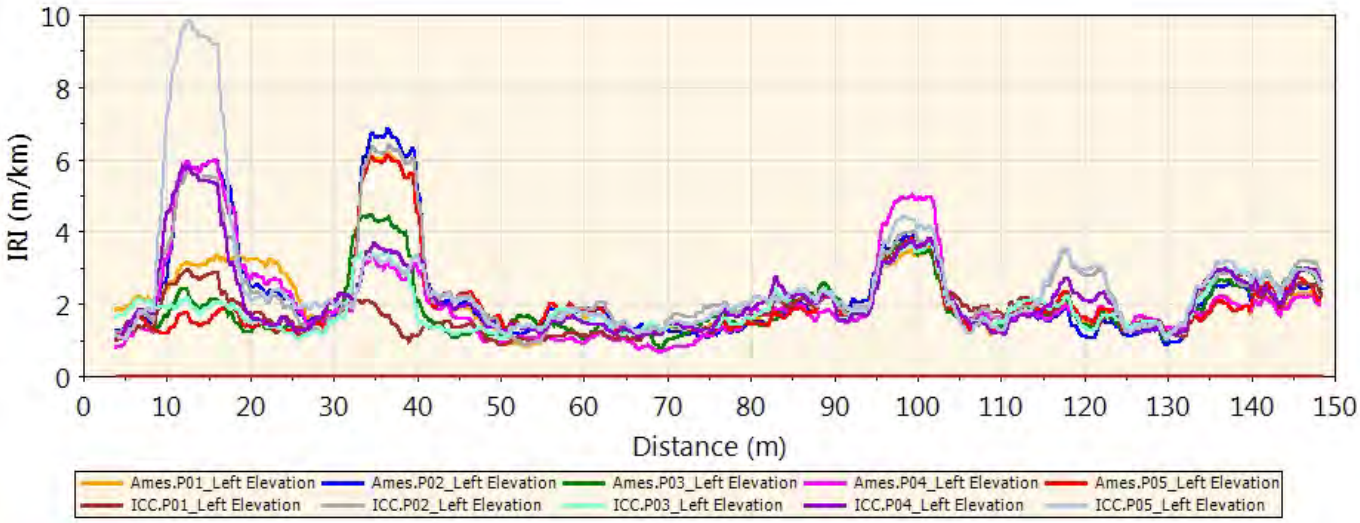

Figure 5.28. Continuous IRI for Western Region, Rough PCC, 65 mph, Left Sensor, Average Difference 0.11 m/km

The continuous IRI plots illustrate that the equipment are similar within the range of wavelengths that impact the IRI because the plots are fairly similar. The values are not identical between all runs; however, the differences are not consistent between the different profilers. The differences observed in these plots are more likely a result of the operator following slightly different paths with each run, particularly on those sections with the most distress such as the rough PCC section used by the Western region.

CHAPTER 6 – CROSS CORRELATION

Cross-correlation is a process to evaluate the agreement between two profiles. The method yields a value ranging from 0 to 100 percent with 0 percent indicating no agreement between the profiles at all and 100 percent indicating exact agreement between profiles.

This evaluation process may be applied to the raw profile data as obtained from the profilers. In our case, based on the observations made from the profile plots in Chapter 4, we know that a cross-correlation of the raw profile data would not yield good result. This lack of correlation between the raw data does not indicate that the profilers cannot provide similar results for ride quality evaluation. Therefore, cross-correlation is generally reviewed in terms of data that has been filtered to remove the influence of wavelengths of roughness that do not impact ride quality.

Cross-correlations can provide an indication of the precision of a single device. Tables 6.1 and 6.2 present the average minimum and maximum cross correlations of runs for a single device. Karamihas recommended that the precision as represented by the cross correlation of a device to itself in multiple runs should have an average value of at least 94 percent for construction quality control.(1)

The average cross correlation for both the Ames and ICC profilers exceeded the 94 percent level for many of the sites. This level of cross correlation was not achieved on all of the sites, but was most likely to be below that level on sites with higher levels of roughness. One important factor to consider is that this level of cross correlation may be very difficult to achieve. A site with any transverse variability may significantly impact the results if the exact same path is not followed in each run. The rough sites tested by both the North region and the Western region were identified as having excessive roughness suggesting that it would be highly unexpected to observe high correlation values on these sites. Both tables suggest that these devices have acceptable levels of precision.

Table 6.1. Results of cross correlation of IRI-filtered data from North Region

Site	Speed	Device	Sensor	Correlation		
				Mean	Minimum	Maximum
Smooth AC	35 mph	Ames	Left	96	94	98
			Right	97	96	98
		ICC	Left	98	97	99
			Right	98	97	99
Rough AC	35 mph	Ames	Left	92	85	99
			Right	96	92	99
		ICC	Left	79	67	87
			Right	77	64	93
	50 mph	Ames	Left	95	91	99
			Right	94	89	98
		ICC	Left	84	71	94
			Right	92	86	97
Rough PCC1	35 mph	Ames	Left	94	89	98
			Right	95	93	97
		ICC	Left	78	67	88
			Right	78	66	88
	50 mph	Ames	Left	94	88	98
			Right	96	95	97
		ICC	Left	91	86	95
			Right	91	83	97
Rough PCC2	35 mph	Ames	Left	98	95	99
			Right	96	94	97
		ICC	Left	89	81	97
			Right	94	90	97
	50 mph	Ames	Left	96	94	98
			Right	96	93	98
		ICC	Left	93	89	96
			Right	93	88	98
Texas Acceptance Section 1	N/A	Ames	Left	87	79	95
			Right	83	65	95
		ICC	Left	87	81	95
			Right	87	76	92
Texas Acceptance Section 2	N/A	Ames	Left	96	92	97
			Right	98	96	99
		ICC	Left	91	87	96
			Right	94	92	97

Table 6.2. Results of cross correlation of IRI-filtered data from Western Region

Site	Speed	Device	Sensor	Correlation		
				Mean	Minimum	Maximum
Smooth AC	35 mph	Ames	Left	89	83	93
			Right	92	89	94
		ICC	Left	89	83	93
			Right	92	86	96
	50 mph	Ames	Left	90	87	93
			Right	94	90	97
		ICC	Left	82	69	91
			Right	90	82	94
Rough AC	35 mph	Ames	Left	76	64	88
			Right	68	55	76
		ICC	Left	80	63	96
			Right	74	68	87
	50 mph	Ames	Left	76	63	96
			Right	74	64	84
		ICC	Left	75	61	90
			Right	76	62	88
Rough PCC	50 mph	Ames	Left	70	54	88
		ICC	Left	53	34	95
			Right	31	13	51
	65 mph	Ames	Left	54	29	89
		ICC	Left	52	30	76
			Right	25	12	54

Cross-correlations of the IRI-filtered data also may be used as an indication of how well the IRI data agree between the two devices over the section. The cross-correlations were limited to a review of five runs for each site at each speed. Table 6.3 presents the average results for the 5 runs for each site and speed by wheelpath from the North region. Table 6.4 presents the results for the runs for each site and speed by wheelpath from the Western region. Three levels of cross-correlation have been identified for profiler certification.(1) The lowest level is a value of 88 percent and is labeled the "Network" level which refers to comparison of a profiler to be used for network-level data collection and a reference device. A "Project" class of comparison is identified as a cross correlation of 94 percent. It should be recognized that in each of these cases, the cross correlation presented is for a comparison of a device to itself or of a device to a reference device. There is very little information available indicating acceptable levels of cross correlation between two inertial profilers.

Table 6.3. Results of cross correlation of IRI-filtered data from North Region

Site	Speed	Sensor	Correlation		
			Mean	Minimum	Maximum
Smooth AC	35 mph	Left	95	94	97
		Right	97	95	98
Rough AC	35 mph	Left	72	53	87
		Right	77	68	86
	50 mph	Left	70	55	85
		Right	81	70	89
Rough PCC1	35 mph	Left	82	77	90
		Right	82	76	88
	50 mph	Left	93	85	98
		Right	94	91	97
Rough PCC2	35 mph	Left	94	88	98
		Right	94	89	98
	50 mph	Left	93	90	97
		Right	90	83	95
Texas Acceptance Section 1	50 mph	Left	86	73	94
		Right	85	61	97
Texas Acceptance Section 2	50 mph	Left	88	78	96
		Right	93	89	98

Table 6.4. Results of cross correlation of IRI-filtered data from Western Region

Site	Speed	Sensor	Correlation		
			Mean	Minimum	Maximum
Smooth AC	35 mph	Left	83	74	90
		Right	91	86	95
	50 mph	Left	84	73	91
		Right	91	86	94
Rough AC	35 mph	Left	78	61	88
		Right	69	55	78
	50 mph	Left	73	57	90
		Right	71	56	88
Rough PCC	50 mph	Left	58	34	85
	65 mph	Left	53	27	85

On average, the cross correlations meet the network level requirement for comparison of 0.88 with the exception of a couple of sites. The maximum cross correlation between the runs does meet this level for all but two of the sites. The rough sections presented the greatest difficulty for the profilers. But, as noted previously, sites with any transverse variability in roughness make it difficult for a profiler to meet this level of correlation as the operator must follow nearly the exact same path with each run.

The data from the Texas Acceptance Sections were used to further review the cross correlations for the equipment. First, the data from the devices were compared against the SurPro that had been used to collect data on these sites. The SurPro data were collected approximately 2 months prior to the collection performed by the Ames and ICC units used in this evaluation. Therefore, the results should not be reviewed expecting the same level of cross correlation as may be found from typical acceptance data. The results of this comparison are shown in table 6.5. These results indicate that the cross correlation of the Ames units with the SurPro are slightly larger than those of the ICC units with the SurPro.

Table 6.5. Results of cross correlation of IRI-filtered data for Texas Acceptance Sections

Site	Device	Sensor	Correlation		
			Mean	Minimum	Maximum
Texas Acceptance Section 1	ICC	Left	80	72	88
		Right	77	66	86
	Ames	Left	75	65	84
		Right	73	54	87
Texas Acceptance Section 2	ICC	Left	83	76	87
		Right	89	86	91
	Ames	Left	93	89	96
		Right	95	93	97

The data for Texas Acceptance Section 2 were further reviewed by examining the cross correlations using a band pass filter to evaluate the profile over a specific range of wavelengths. A band pass filter removes wavelengths outside of the range specified. Table 6.6 presents the results of this comparison for the Ames and ICC profilers. The table shows that the correlation is acceptable in the range of wavelengths from 5 to 20 m. The correlation is slightly lower at wavelengths less than 5 m and at wavelengths from 20 to 25 m. The correlation deteriorates greatly past 25 m. This deterioration suggests that the different long wavelength filters used by the two units impacts the data in this range of wavelengths.

Table 6.6. Results of cross correlation between Ames and ICC units for bandpass filtered data from Texas Acceptance Section 2

Wavelength Range	Sensor	Correlation		
		Mean	Minimum	Maximum
1.52 to 5 m	Left	86	67	98
	Right	94	91	98
5 to 10 m	Left	90	79	98
	Right	94	88	99
10 to 15 m	Left	90	83	98
	Right	92	86	98
15 to 20 m	Left	93	85	99
	Right	94	89	98
20 to 25 m	Left	95	89	99
	Right	98	93	99
25 to 30.48 m	Left	98	95	99
	Right	98	96	99

Table 6.7 provides the cross correlation of the Ames to the SurPro unit and table 6.8 provides the cross correlation of the ICC to the SurPro unit. In reviewing these tables, it may be seen that the both units have a lesser correlation with the SurPro unit at the short wavelengths (1.52 m to 5 m).

Table 6.7. Results of cross correlation between Ames and SurPro units for bandpass filtered data from Texas Acceptance Section 2

Wavelength Range	Sensor	Correlation		
		Mean	Minimum	Maximum
1.52 to 5 m	Left	69	57	79
	Right	73	53	88
5 to 10 m	Left	87	78	92
	Right	90	82	97
10 to 15 m	Left	78	73	82
	Right	94	91	97
15 to 20 m	Left	85	84	86
	Right	90	89	92
20 to 25 m	Left	94	93	94
	Right	95	94	96
25 to 30.48 m	Left	97	96	98
	Right	96	95	97

Table 6.8. Results of cross correlation between ICC and SurPro units for bandpass filtered data from Texas Acceptance Section 2

Wavelength Range	Sensor	Correlation		
		Mean	Minimum	Maximum
1.52 to 5 m	Left	74	64	82
	Right	90	89	92
5 to 10 m	Left	87	81	90
	Right	90	85	93
10 to 15 m	Left	94	89	97
	Right	86	82	89
15 to 20 m	Left	96	92	99
	Right	94	92	94
20 to 25 m	Left	97	94	98
	Right	95	92	96
25 to 30.48 m	Left	97	95	98
	Right	93	91	95

An additional comparison was performed to review the correlations observed between the ICC and Ames units. Comparisons were made between different profiler makes as part of purchases of profilers for the program in 1996 and 2002. A cross correlation analysis was not conducted as part of these comparisons, but the data were available to perform the analysis at this time.

Table 6.9 presents the cross correlations between the original KJ Law DNC690 profilers and the KJ Law T6600 profilers purchased in 1996 for data collected by the regions on each of four sections. This change in equipment marked a change in data collection frequency for the profile data from 150 mm to 25 mm. For the data collected in table 6.9, the regions used a setting to collect profile at 150-mm intervals rather than the 25-mm interval.

Table 6.9 Cross Correlation between KJ Law DNC690 and T6600 profilers

Region	Site	Sensor	Correlation			IRI
			Mean	Minimum	Maximum	
North Atlantic	1A	Left	74	63	85	0.80
		Right	87	84	91	0.86
	2A	Left	62	54	71	2.32
		Right	67	58	77	1.86
	3A	Left	76	69	83	1.21
		Right	81	75	86	1.32
	4A	Left	84	80	88	1.85
		Right	92	87	95	2.11
North Central	1A	Left	64	53	78	1.03
		Right	85	80	89	1.07
	2A	Left	80	67	89	3.91
		Right	92	85	97	4.81
	3A	Left	85	82	88	1.09
		Right	94	91	96	1.06
	4A	Left	86	80	91	2.66
		Right	48	10	93	3.34
South	1A	Left	89	85	92	0.71
		Right	79	73	86	0.71
	2A	Left	47	41	53	1.75
		Right	37	33	45	1.82
	3A	Left	83	79	87	2.07
		Right	89	85	92	2.34
	4A	Left	87	82	91	1.77
		Right	90	88	92	1.70
West	1A	Left	86	84	88	0.77
		Right	92	90	95	0.92
	2A	Left	7	3	10	2.99
		Right	82	66	97	2.53
	3A	Left	86	80	90	1.13
		Right	85	78	93	1.05
	4A	Left	89	84	94	2.27
		Right	90	86	96	2.42

Table 6.9 illustrates that there are six of the correlations of 90 percent or larger, but the majority of the values are in the range of 70 to 90 percent and there are a few values below 50 percent.

Table 6.10 provides the cross correlations between the KJ Law T6600 and the ICC units purchased in 2002. This comparison shows eight correlations of 90 percent of greater, but the majority of the results are in the 70 to 80 percent range.

Table 6.10 Cross Correlations between the KJ Law T6600 and ICC profilers

Region	Site	Sensor	Correlation			IRI
			Mean	Minimum	Maximum	
North Atlantic	245807	Left	77	71	84	1.52
		Right	82	79	87	1.58
	251002	Left	60	41	82	4.10
		Right	66	50	83	1.49
	360801	Left	92	90	95	1.13
		Right	91	87	93	1.11
	361011	Left	75	58	92	0.93
		Right	81	72	92	0.91
	872811	Left	74	64	84	1.60
		Right	76	64	88	1.67
North Central	17A001	Left	89	81	92	1.02
		Right	94	91	96	1.24
	17B002	Left	90	86	95	2.79
		Right	93	88	96	2.84
	17B003	Left	84	80	91	1.10
		Right	82	78	86	1.18
	17B004	Left	94	91	97	4.07
		Right	96	94	98	4.18
West	067454	Left	81	73	90	2.34
		Right	82	77	91	2.35
	069107	Left	59	44	80	2.70
		Right	71	64	85	2.53
	169034	Left	79	74	88	1.83
		Right	84	69	91	2.04
	320110	Left	89	85	91	0.60
		Right	91	89	93	0.77
	320209	Left	74	69	79	1.16
		Right	78	73	84	1.08

The historical data suggests that the cross correlations observed between the ICC and Ames profilers are quite similar to, if not better than, those observed previously. The lower correlations occur on the sections with higher IRIs as shown in figure 6.1. The horizontal line in figure 6.1 illustrates the level of acceptable cross correlation as defined in this review at a value of 88 percent. Figure 6.1 also illustrates how similar the correlations are between the different equipment changes. This figure also illustrates that the lowest cross correlations were observed with the first equipment change from the KJ Law DNC 690 profilers to the KJ Law T6600 profilers.

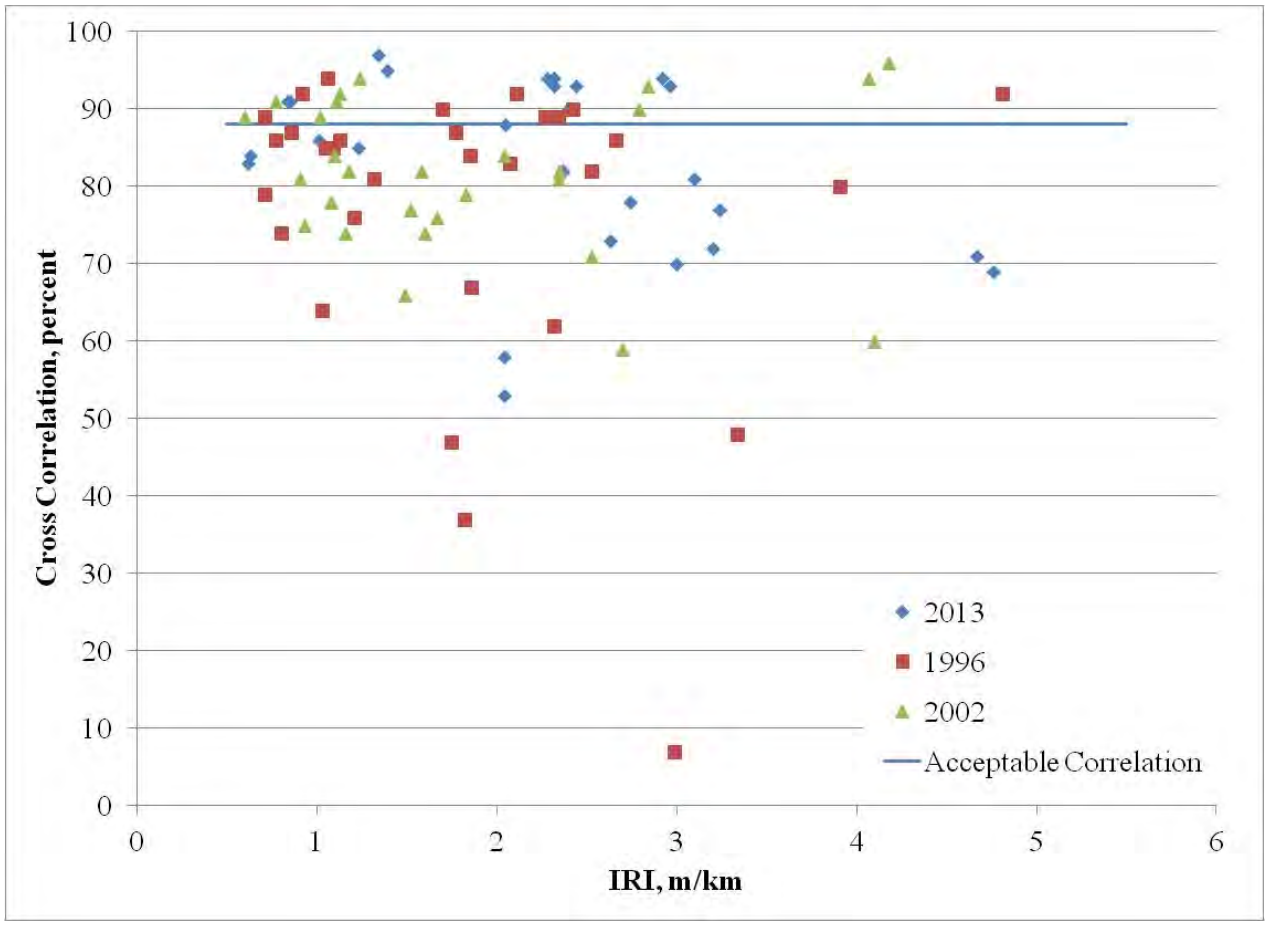

Figure 6.1. Comparison of Cross Correlation and IRI

CHAPTER 7 – POWER SPECTRAL DENSITY

A power spectral density (PSD) plot shows the importance of the wavelength in a profile. The profiles are decomposed into a series of sinusoids to show how the variance is distributed over the wavelengths. Figures 7.1 through 7.18 present PSD plots for the data collected by the North region using both profilers and figures 7.19 through 7.28 present PSD plots for the data collected by the Western region using both profilers. For this comparison, the first run for each profiler on each site was used to better view the differences between the two systems.

The PSD identifies the size of the features captured by the measured profile. No inertial profiler can accurately capture very long features such as hills; therefore, most manufacturers implement a filter to eliminate long wavelength content from the collected data. As identified in Chapter 3, these two manufacturers use a different approach for filtering out the long wavelength content that is not accurately captured by the equipment. Additionally, the equipment has a limit on the short wavelength content it is able to capture. The short wavelength measurement is limited by the data collection interval used by the equipment.

The IRI is most impacted by wavelengths ranging from 1.3 to 30 m. The desire is to see a close match between the lines within this range of wavelengths. Karamihas has shown that the IRI may be impacted by wavelengths ranging from 0.4 to 137.8 m.(1) As an example, Figure 7.1 shows generally good agreement in wavelengths ranging from 0.3 to 30 m, but as the wavelengths increase in length, the difference in the equipment increases. This observation is consistent with that from the cross correlations where lower cross correlations were observed for wavelengths ranging from 25 to 30.48 m.

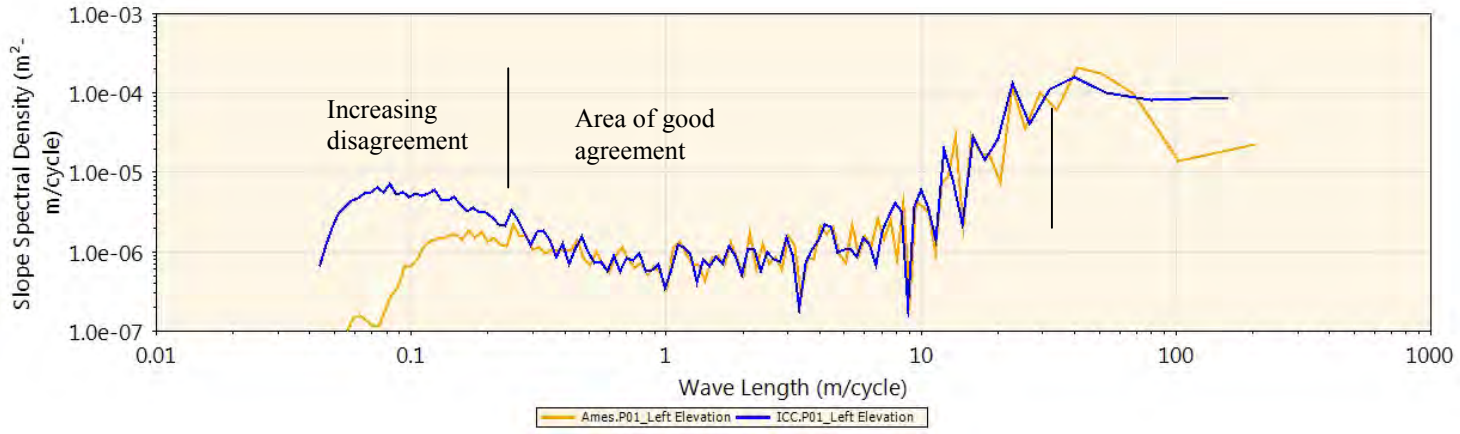

Figure 7.1. PSD Plot of North Region Smooth AC, 35 mph, Left Sensor

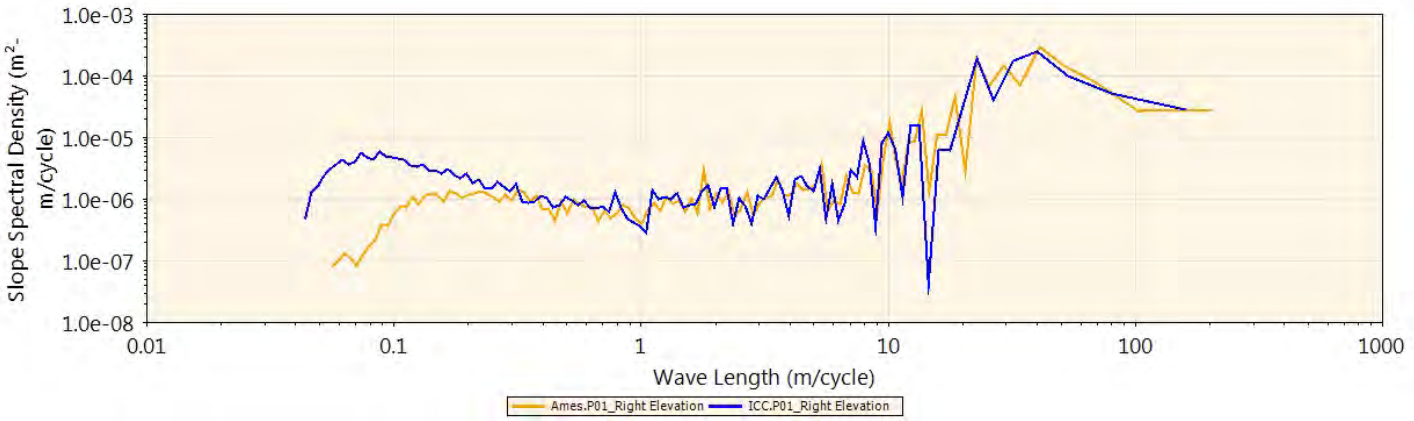

Figure 7.2. PSD Plot of North Region Smooth AC, 35 mph, Right Sensor

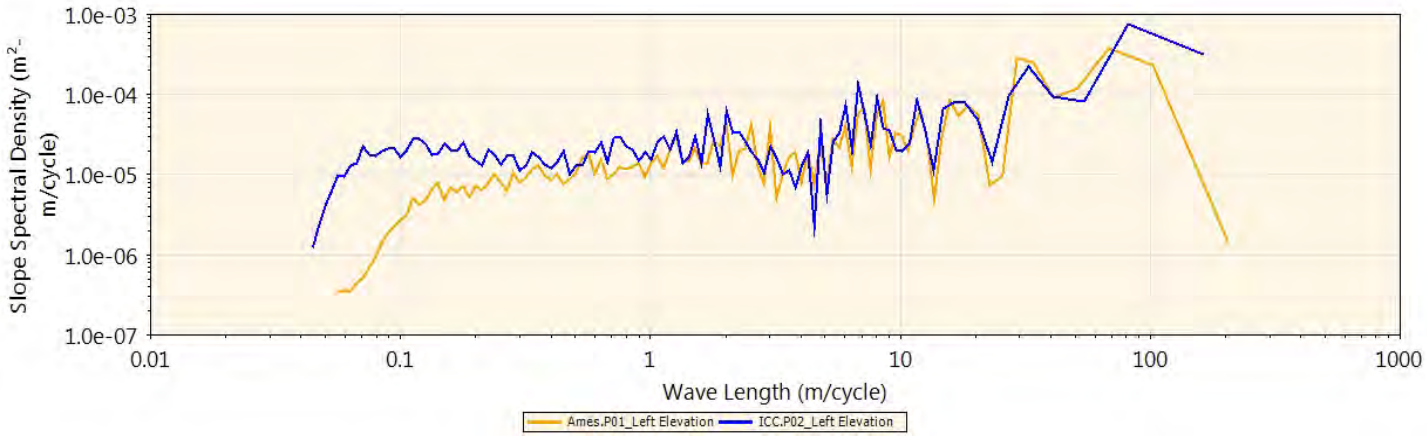

Figure 7.3. PSD Plot of North Region Rough AC, 35 mph, Left Sensor

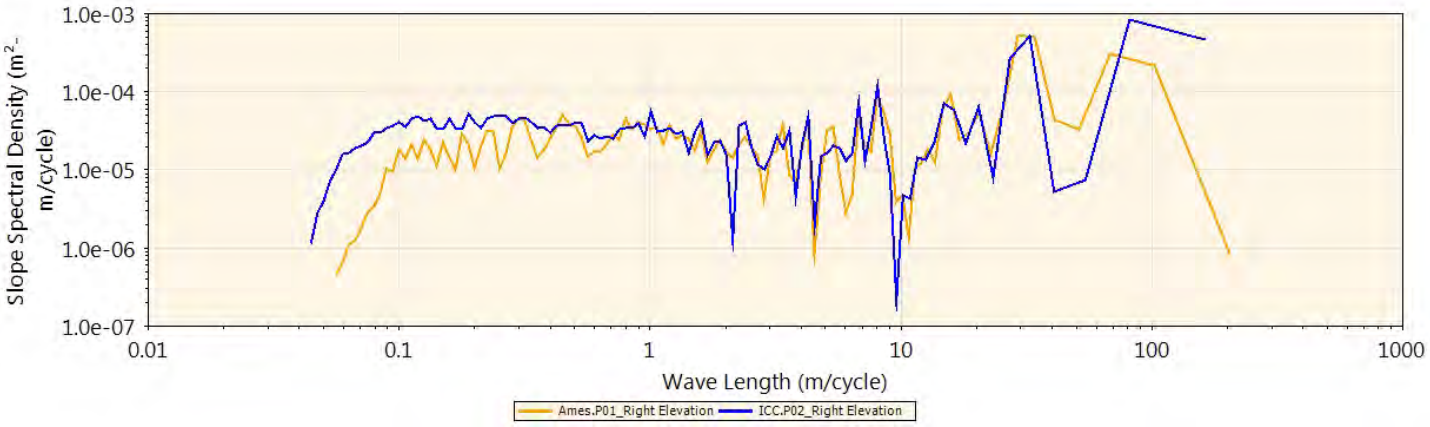

Figure 7.4. PSD Plot of North Region Rough AC, 35 mph, Right Sensor

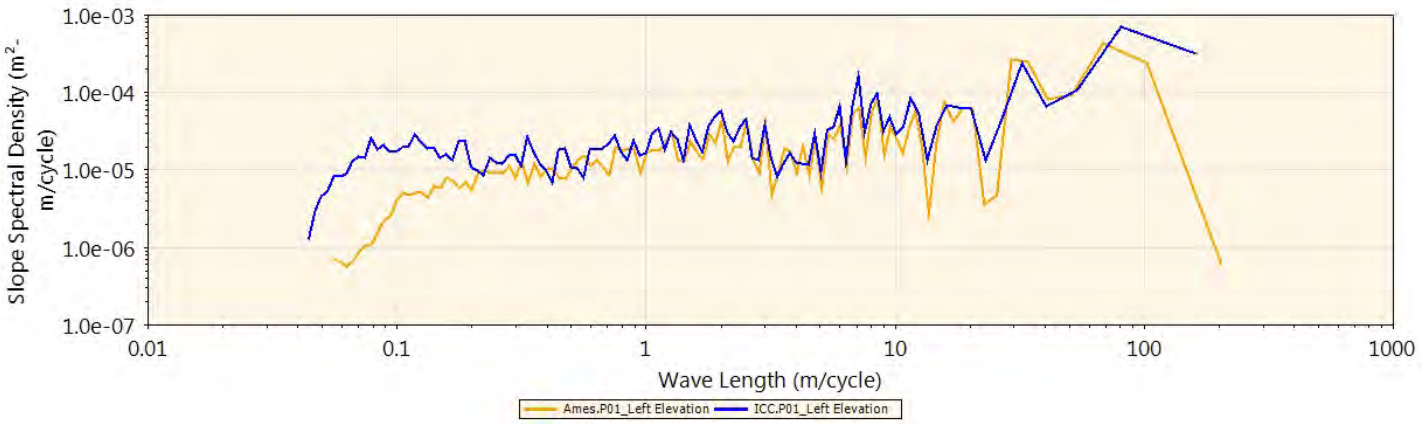

Figure 7.5. PSD Plot of North Region Rough AC, 50 mph, Left Sensor

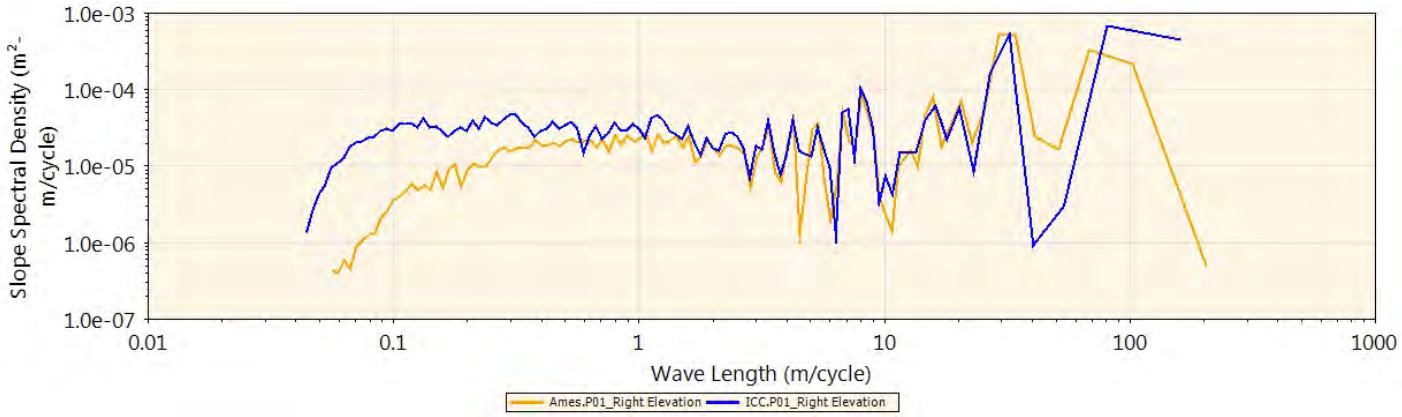

Figure 7.6. PSD Plot of North Region Rough AC, 50 mph, Right Sensor

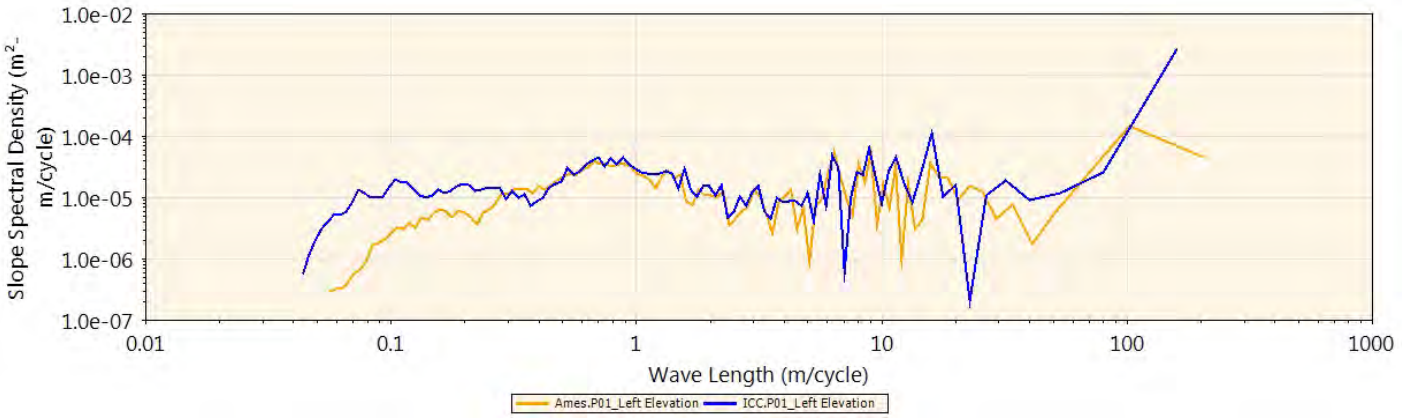

Figure 7.7. PSD Plot of North Region Rough PCC Section 1, 35 mph, Left Sensor

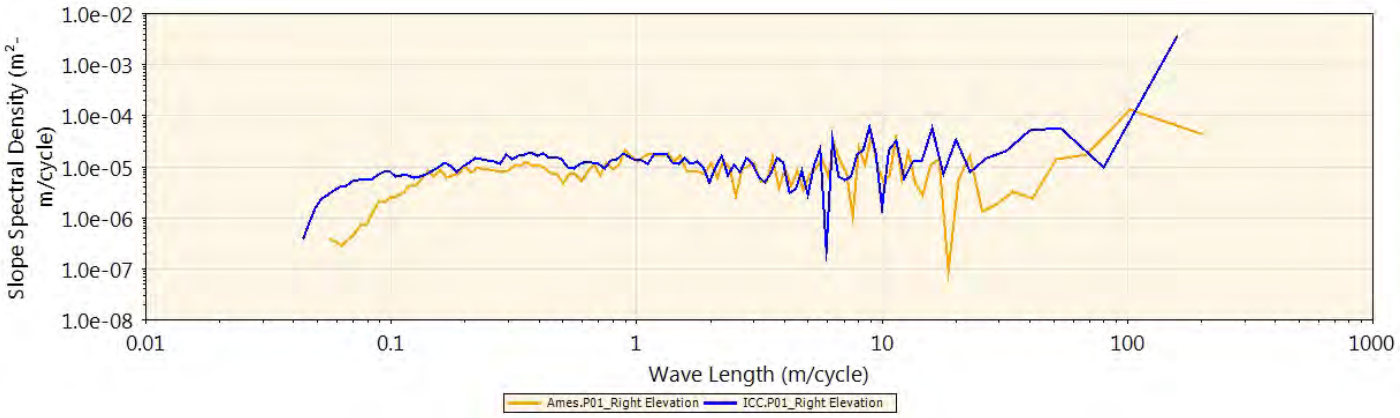

Figure 7.8. PSD Plot of North Region Rough PCC Section 1, 35 mph, Right Sensor

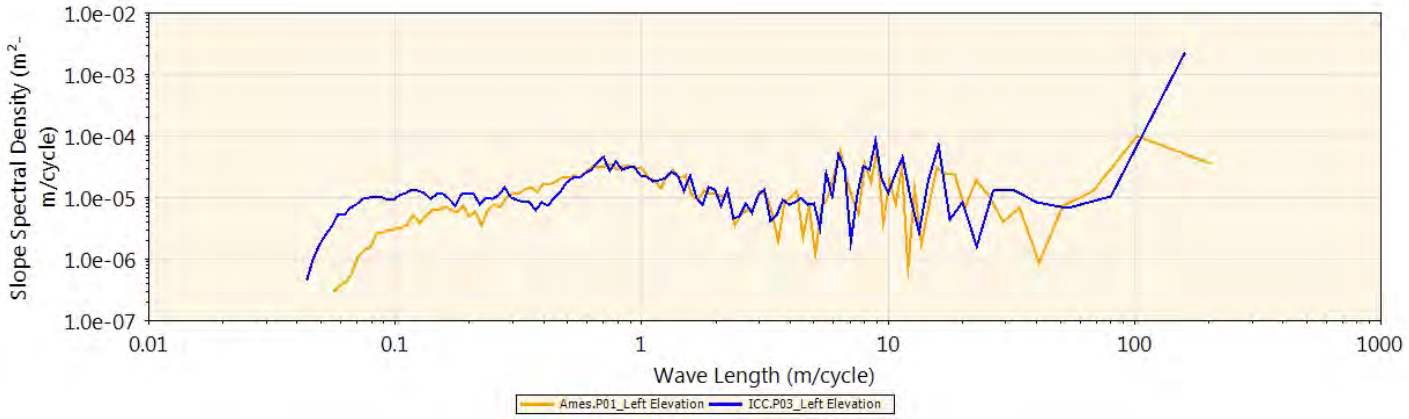

Figure 7.9. PSD Plot of North Region Rough PCC Section 1, 50 mph, Left Sensor

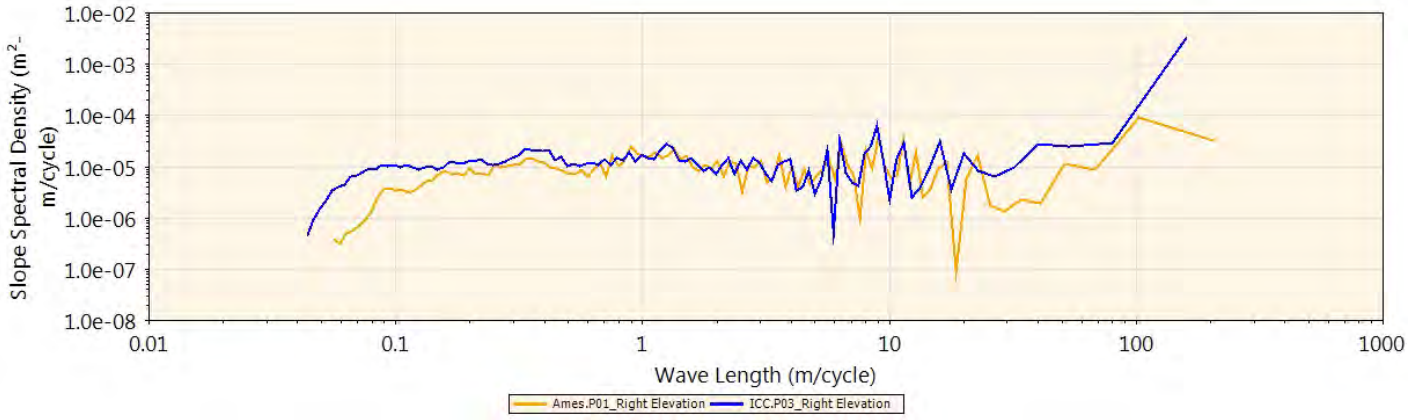

Figure 7.10. PSD Plot of North Region Rough PCC Section 1, 50 mph, Right Sensor

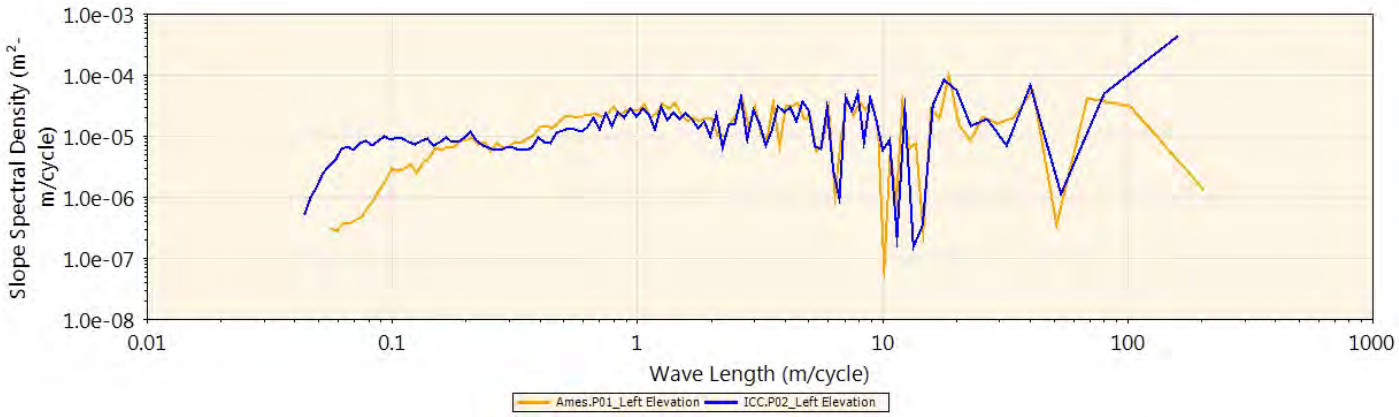

Figure 7.11. PSD Plot of North Region Rough PCC Section 2, 35 mph, Left Sensor

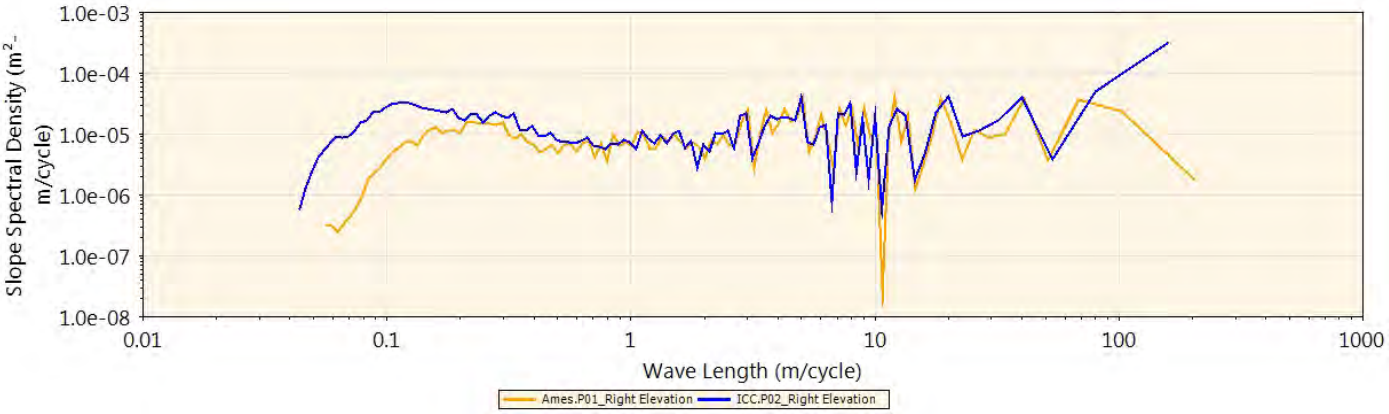

Figure 7.12. PSD Plot of North Region Rough PCC Section 2, 35 mph, Right Sensor

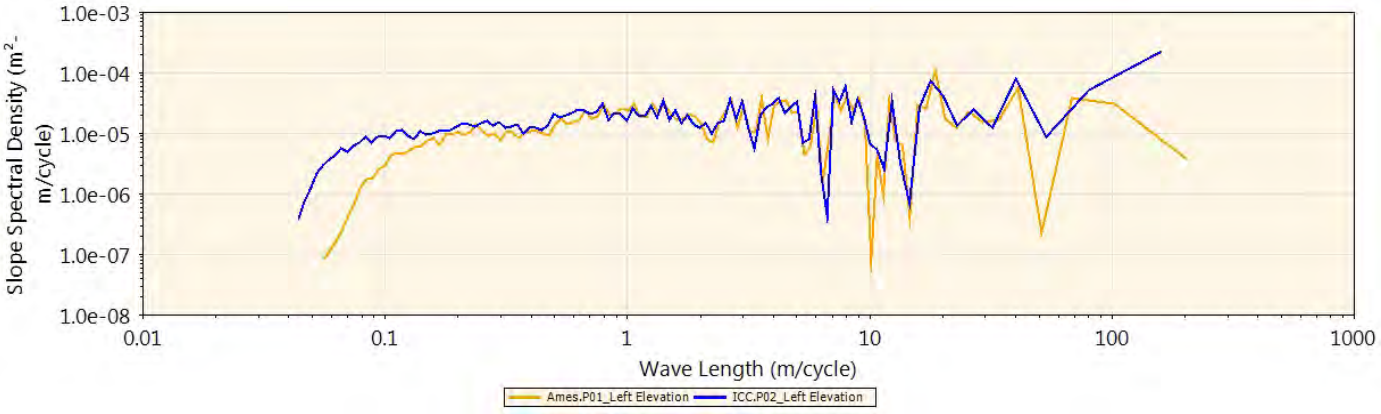

Figure 7.13. PSD Plot of North Region Rough PCC Section 2, 50 mph, Left Sensor

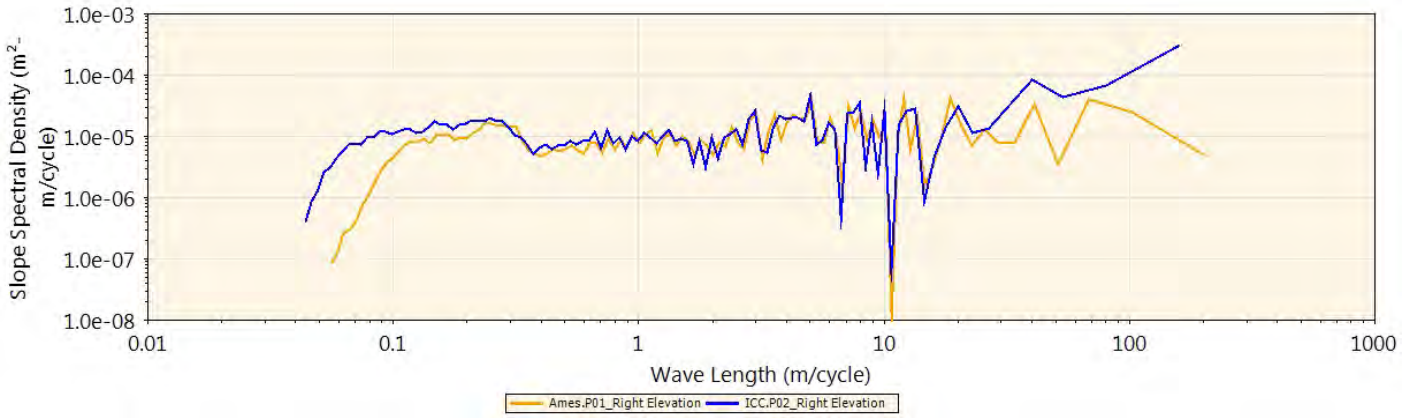

Figure 7.14. PSD Plot of North Region Rough PCC Section 2, 50 mph, Right Sensor

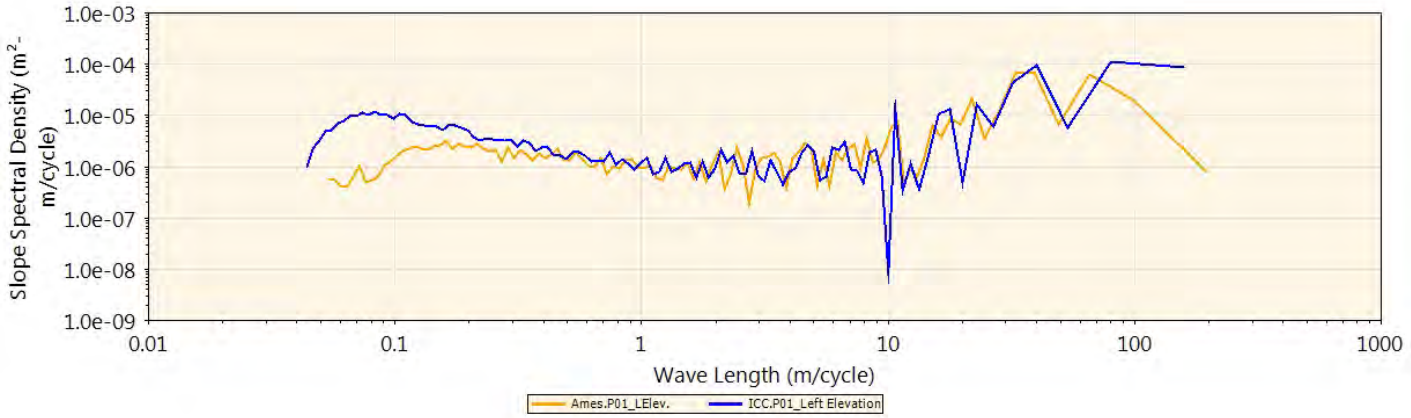

Figure 7.15. PSD Plot of North Region Texas Acceptance Section 1, 50 mph, Left Sensor

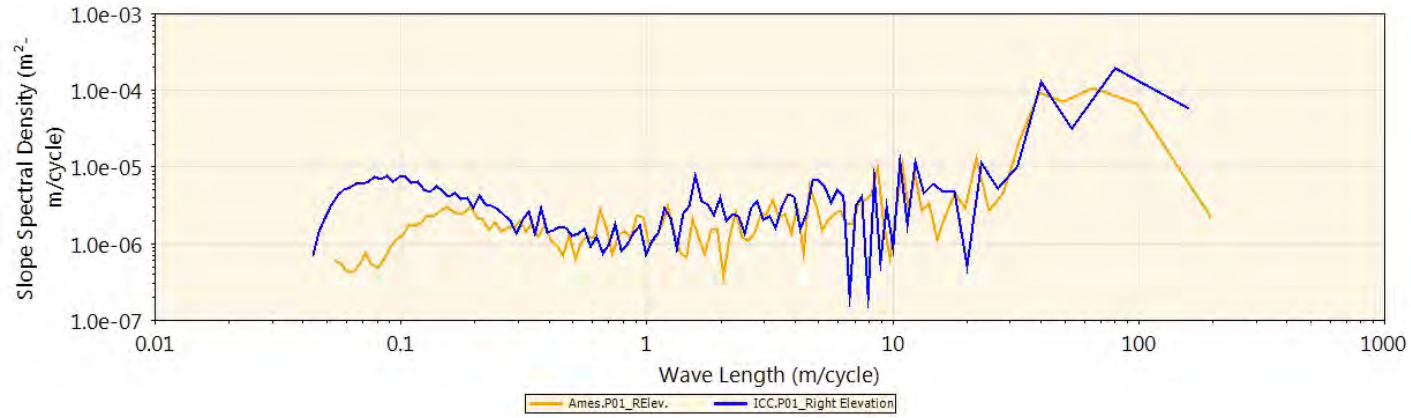

Figure 7.16. PSD Plot of North Region Texas Acceptance Section 1, 50 mph, Right Sensor

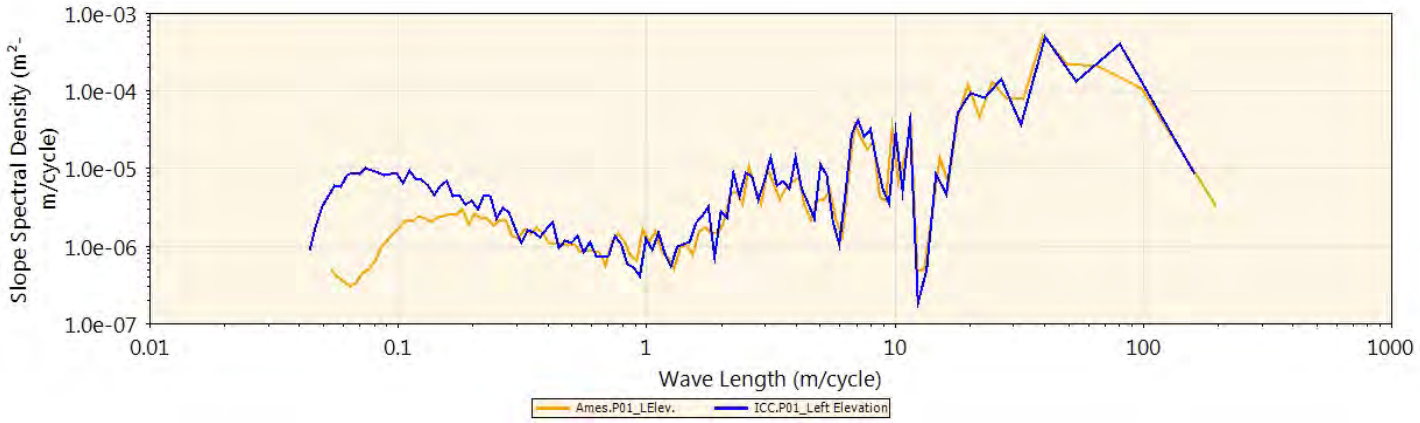

Figure 7.17. PSD Plot of North Region Texas Acceptance Section 2, 50 mph, Left Sensor

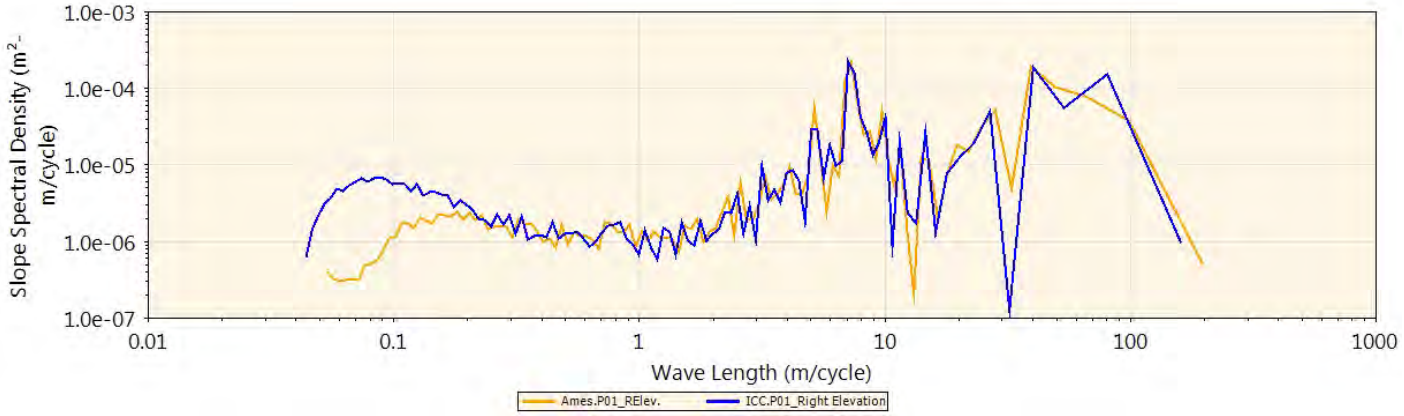

Figure 7.18. PSD Plot of North Region Texas Acceptance Section 2, 50 mph, Right Sensor

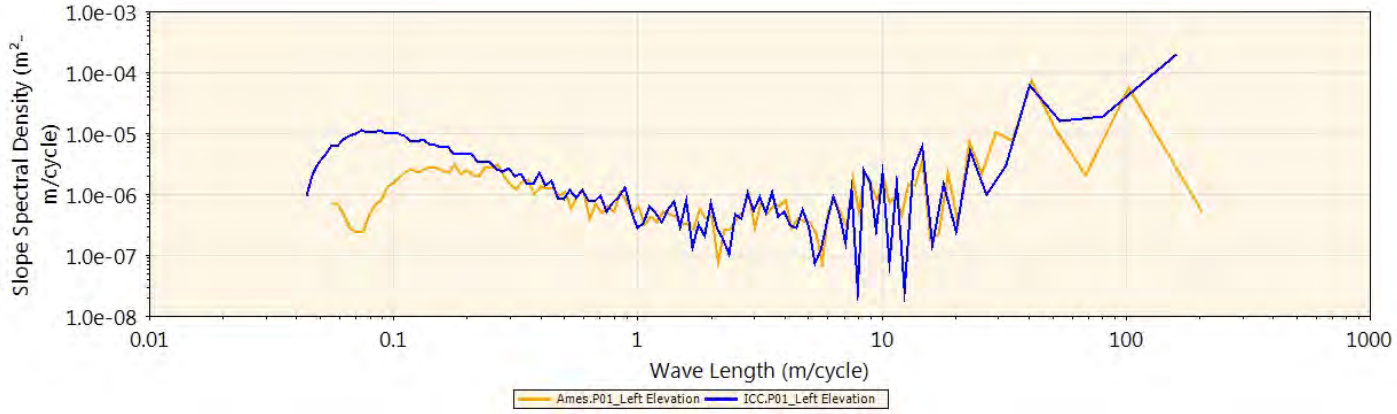

Figure 7.19. PSD Plot of Western Region Smooth AC, 35 mph Left Sensor

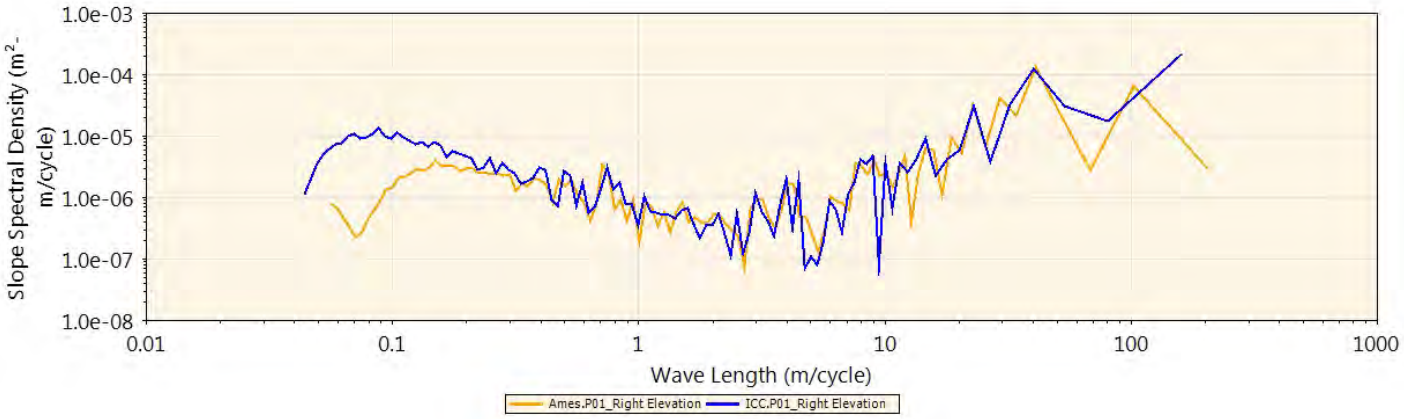

Figure 7.20. PSD Plot of Western Region Smooth AC, 35 mph, Right Sensor

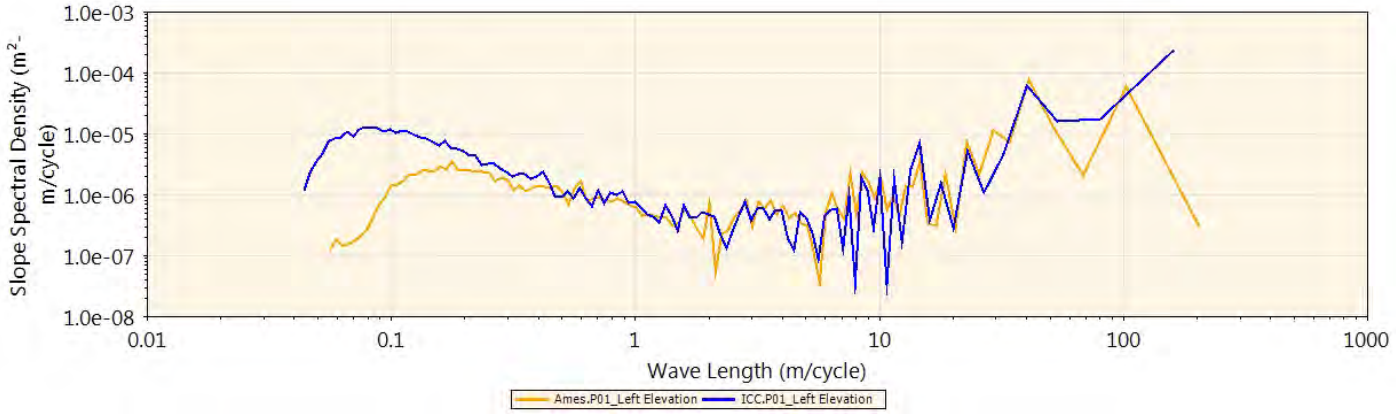

Figure 7.21. PSD Plot of Western Region Smooth AC, 50 mph, Left Sensor

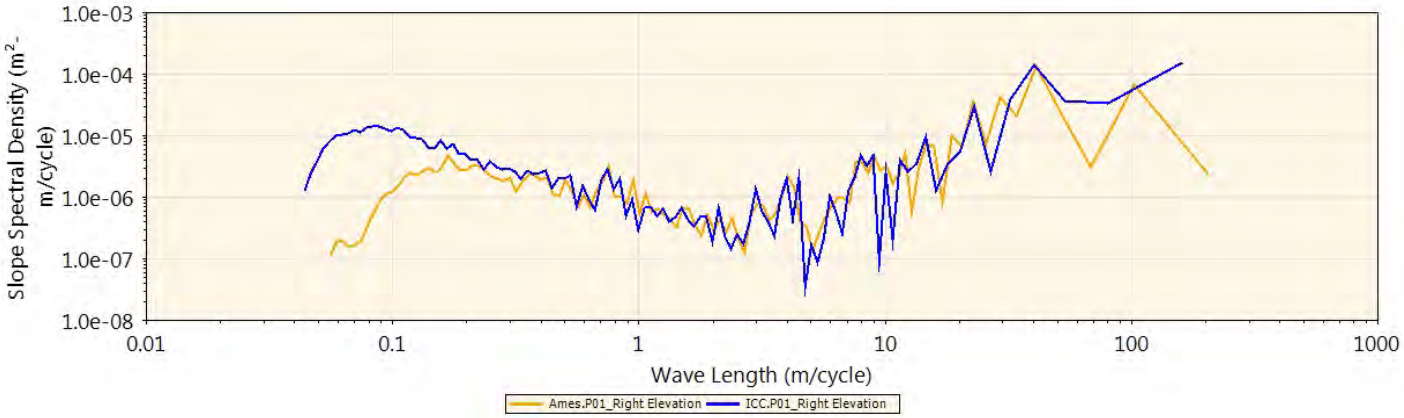

Figure 7.22. PSD Plot of Western Region Smooth AC, 50 mph, Right Sensor

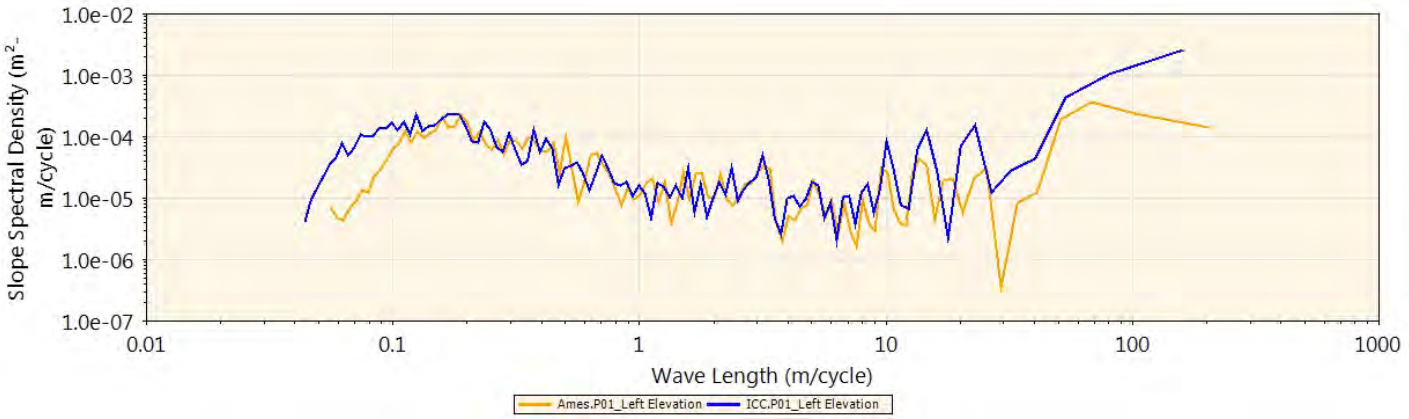

Figure 7.23. PSD Plot of Western Region Rough AC, 35 mph, Left Sensor

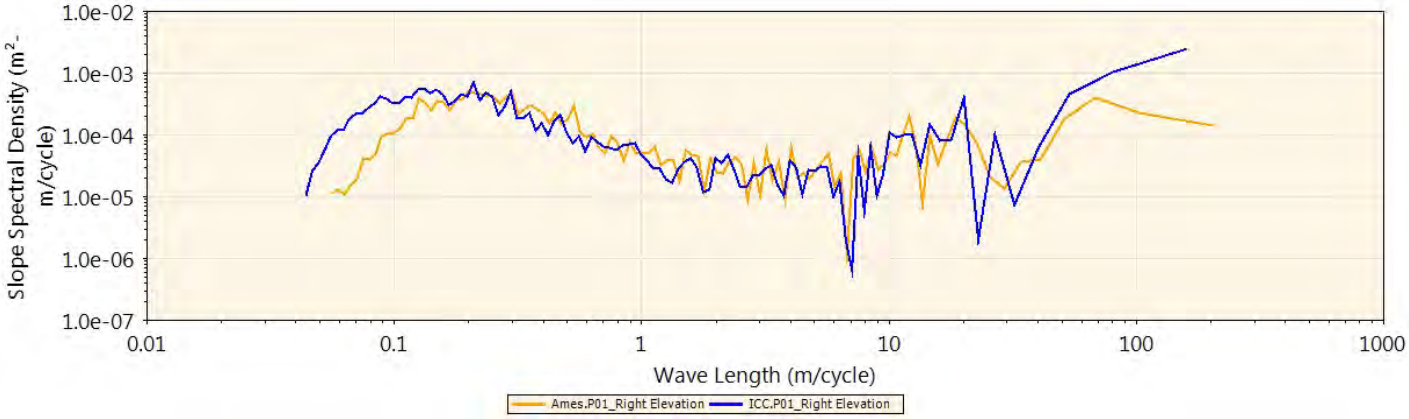

Figure 7.24. PSD Plot of Western Region Rough AC, 35 mph, Right Sensor

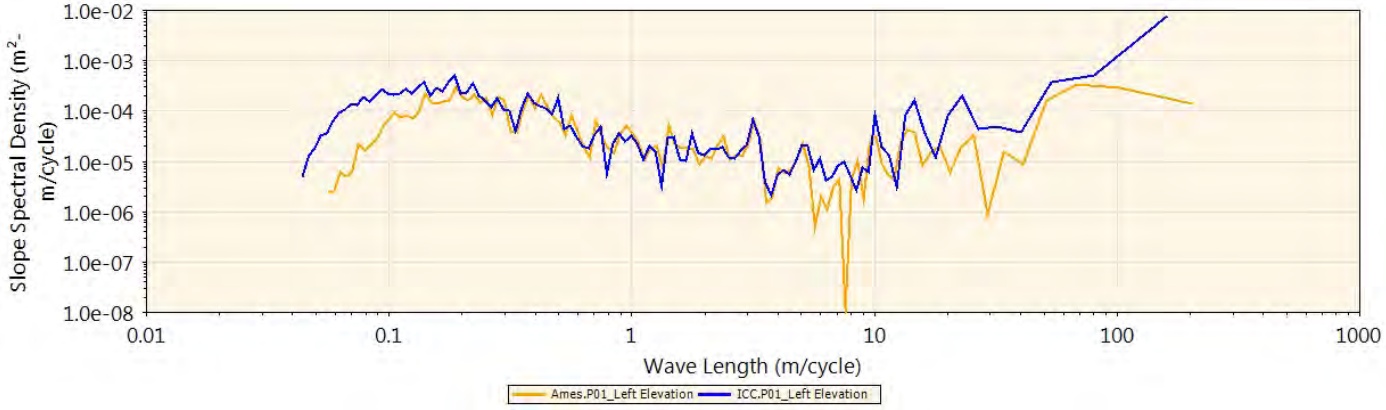

Figure 7.25. PSD Plot of Western Region Rough AC, 50 mph, Left Sensor

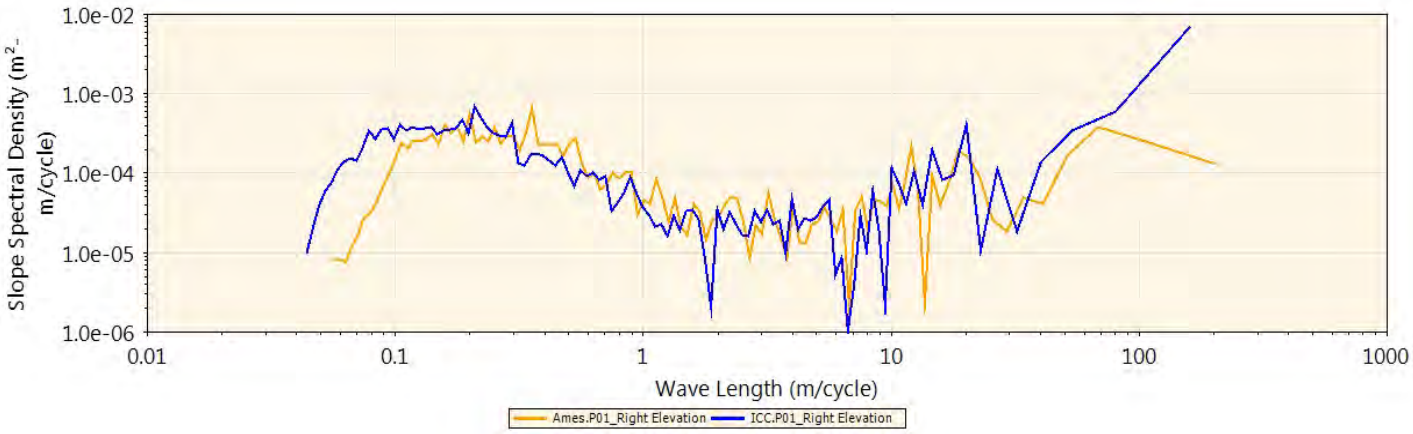

Figure 7.26. PSD Plot of Western Region Rough AC, 50 mph, Right Sensor

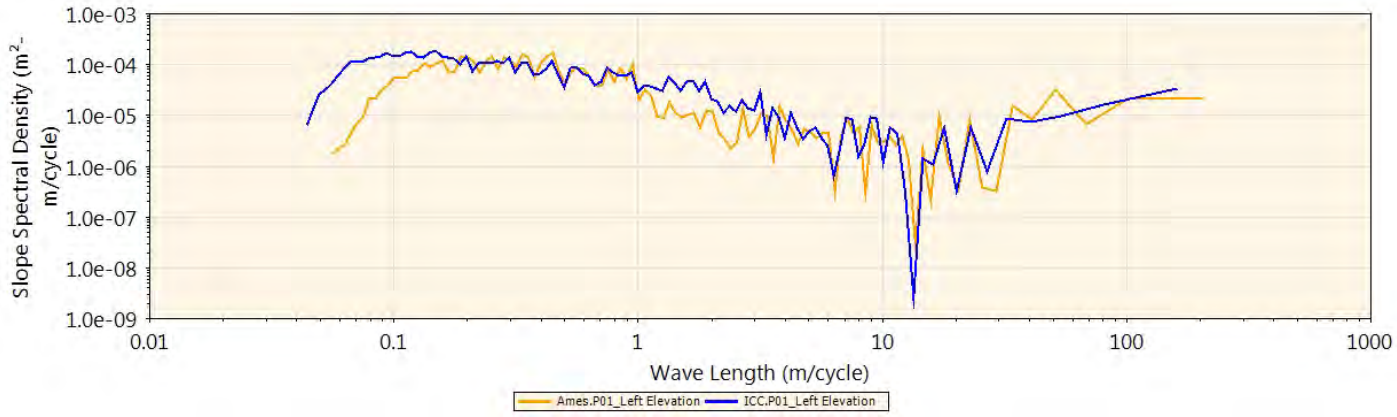

Figure 7.27. PSD Plot of Western Region Rough PCC, 50 mph, Left Sensor

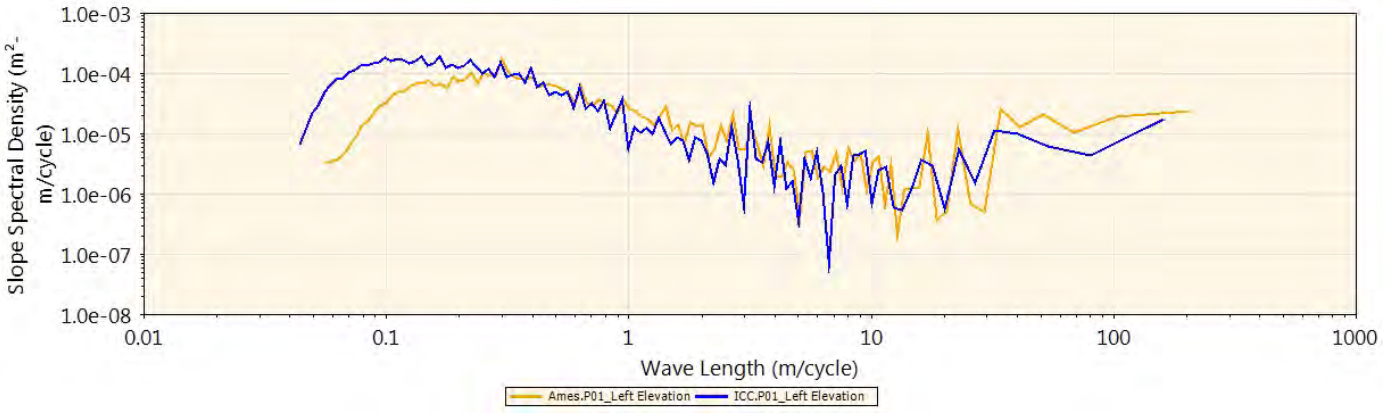

Figure 7.28. PSD Plot of Western Region Rough PCC, 65 mph, Left Sensor

The observation from Figure 7.1 is consistent for all of the PSDs. There are a couple of graphs such as figure 7.5 which show disagreement in the shorter wavelength range. Overall, the greatest differences are observed starting at wavelengths of approximately 50 to 100 m and larger. Generally, at wavelengths below 50 m, the PSD plots show generally good agreement in wavelengths for the two profilers. Also, there is some difference in the wavelengths less than 0.2

m. This difference appears because of the anti-aliasing applied by the Ames Engineering profiler, while the ICC profilers did not apply this anti-aliasing. From these graphs, the devices provide a similar response for the range of wavelengths which most impact the IRI.

CHAPTER 8 – SUMMARY AND RECOMMENDATIONS

Data were collected using the Ames profiler and the ICC profiler by the North region on four sections. Additionally, data were collected using both systems by the Western region on three sections. Data collection involved sites with differing levels of roughness and two speeds of data collection were used on all but one site.

Several methods were used to compare the profilers including comparisons of IRI statistics, reviews of plots of the profile data, comparison of plots of continuous IRI, cross-correlation of IRI-filtered profile data, and comparisons of PSD plots. The following conclusions were drawn from these comparisons:

- The IRI statistics indicated that in the North region 5 out of 6 measurement passes on the AC surfaced pavement test sections resulted in statistically significant average levels of computed IRI between the measurement devices. The average difference in IRI was also judged to have significant engineering differences.

- For the Western region profiler comparison, significant statistical differences were indicated for only the right wheelpath sensor on the smooth AC test section at a measurement speed of 35-mph.

- Applying the engineering based test of the significance of differences, five combinations of the North region identified as having statistical significance was found to be not significant, and the single combination from the West region identified as stiatistically significant are not significant.

- The profile elevation plots show an inconsistency between the two profilers, but based on the plots alone, it is impossible to identify the source of the inconsistency and the impact to the IRI.

- Plots of the continuous IRI illustrate that the inconsistencies observed in the profile plots do not translate to consistent differences in the IRI.

- The mean cross-correlation levels for six of the sites and speeds were above the established level of acceptance of 88 percent. All but three of the site-speed combinations had a maximum cross correlation exceeding this level.

- The cross-correlations observed between the ICC and Ames profilers are consistent with the cross-correlations that may be observed from prior equipment comparison, i.e., between the KJ Law DNC690 and T6600, and between the KJ Law T6600 and the ICC profilers.

- Detailed review of the cross correlations by applying a bandpass filter illustrates that the largest differences were in the data in the short wavelength range. This difference is likely due to the difference in the filter applied by the two units.

- The PSD plots indicate that the primary difference in the units is in the data characterizing wavelengths longer than 50 m and shorter than 0.2 m. Generally, the units compare well within the range of wavelengths which have the largest impact on IRI.

This review indicates that the differences observed in IRI should not be expected to be significant between the two units. However, the profiler data collected by the units may be quite different. The differences in the Ames and ICC profilers are similar to the differences observed between prior models of equipment. The implication is that the development of any future indices may be impacted by these equipment changes.

The following recommendations are made for additional investigation to be conducted:

- The analyses show that the differences observed between the Ames and ICC profilers were primarily caused by the short wavelength roughness. In order to understand the impact of these differences, it will be necessary to gain additional understanding of the differences in the filters used by the devices.

- The AASHTO Standard Specification for Inertial Profiler M328 requires profilers to be accurate over a range of wavelengths from 0.15 to 91.4 m in length. The acceptance data for the Ames profilers should be reviewed to determine that these requirements were met for the short wavelength data.

- One of the difficulties in reviewing the data occurred because the sites identified as rough were outside the capabilities of the equipment to measure. Future comparisons conducted by the regions should have definitive specifications for smooth and rough. For example, AASHTO Standard R56 identifies smooth sections as having an IRI from 0.47 to 1.18 m/km and medium-rough as an IRI up to 3.16 m/km.

REFERENCES

1. Karamihas, S.M., *Critical Profiler Accuracy Requirements*, University of Michigan Transportation Research Institute, Ann Arbor, Michigan, August 2005.